Strong $z \sim 0.5$ O vi absorption towards PKS 0405$-$123: implications for ionization and metallicity of the Cosmic Web

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Abstract
We present observations of the intervening O vi absorption-line system at $z_{\text{abs}} = 0.495\,096$ towards the quasi-stellar object (QSO) PKS 0405$-$123 ($z_{\text{em}} = 0.5726$) obtained with the Far Ultraviolet Spectroscopic Explorer and Space Telescope Imaging Spectrograph on board the Hubble Space Telescope. In addition to strong O vi, with log $N(O\,\text{vi}) = 14.47 \pm 0.02$, and moderate $\text{H}1$, with log $N(\text{H}1) = 14.29 \pm 0.10$, this absorber shows absorption from $\text{C}\,\text{ii}$, $\text{N}\,\text{iv}$, $\text{O}\,\text{iv}$ and $\text{O}\,\text{v}$, with upper limits for another seven ions. The large number of available ions allows us to test ionization models usually adopted with far fewer constraints. We find that the observed ionic column densities cannot be matched by single-temperature collisional ionization models, in or out of equilibrium. Photoionization models can match all of the observed column densities, including O vi. If one assumes photoionization by an ultraviolet (UV) background dominated by QSOs, the metallicity of the gas is $[\text{O}/\text{H}] \approx -0.15$, while if one assumes a model for the UV background with contributions from ionizing photons escaping from galaxies the metallicity is $[\text{O}/\text{H}] \approx -0.62$. Both give $[\text{N}/\text{O}] \sim -0.6$ and $[\text{C}/\text{H}] \sim -0.2$ to $-0.1$, though a solar C/O ratio is not ruled out. The choice of ionizing spectrum is poorly constrained and leads to systematic abundance uncertainties of $\approx 0.5$ dex, despite the wide range of available ions. Multiphase models with a contribution from both photoionized gas (at $T \sim 10^4\,\text{K}$) and collisionally ionized gas (at $T \sim (1-3) \times 10^5\,\text{K}$) can also match the observations for either assumed UV background giving very similar metallicities. We do not detect Ne viii or Mg x absorption. The limit on Ne viii/O vi $< 0.21$ ($3\sigma$) is the lowest yet observed. Thus, this absorber shows no firm evidence of the ‘warm-hot intergalactic medium’ at $T \sim (0.5-3) \times 10^5\,\text{K}$ thought to contain a significant fraction of the baryons at low redshift. The O vi in this system is not necessarily a reliable tracer of the warm-hot intergalactic medium given the ambiguity in its origins. We present limits on the total column of warm-hot gas in this absorber as a function of temperature. This system would be unlikely to provide detectable X-ray absorption in the ions O iv or O vii even if it resided in front of the brighter X-ray sources in the sky.

Key words: intergalactic medium – quasars: absorption lines – quasars: individual: PKS 0405$-$123.

1 INTRODUCTION

The baryon density of the universe, $\Omega_b$, is a fundamental quantity in cosmology, and identifying the location and physical state of the baryons is a focus of significant work (see Prochaska & Tumlinson 2009 for a recent review). A census of luminous, emitting baryons in the universe falls short of the total baryon density of the universe determined from other means. Various methods of calculating the baryon density are in good agreement, including the comparison of primordial deuterium measurements with big bang
nucleosynthesis (e.g. Kirkman et al. 2003; O'Meara et al. 2006), and cosmic microwave background studies with the new Wilkinson Microwave Anisotropy Probe (WMAP) measurements (e.g. Spergel et al. 2007). At high redshift, baryonic matter traced in emission falls short of the total baryon budget because most of the baryons reside and can be found within the cool, photoionized intergalactic medium (IGM) of the Lyα forest (LAF; e.g. Rauch et al. 1998). At lower redshift, z ≤ 0.5, the census of stars and gas in galaxies, galaxies and gas in clusters, etc., still falls short of Ω₂, as emphasized by a number of researchers (Perci & Salucci 1992; Fukugita, Hogan & Peebles 1998). This baryon deficit persists even if the cool, photoionized LAF is included. The emitting components contribute only ~0.1Ω₂ (Prochaska & Tumlinson 2009), while including the LAF may increase this to ~0.3Ω₂ (e.g. Penton, Stocke & Shull 2004; Lehner et al. 2007; Danforth & Shull 2008), though with significant uncertainty.

Thus, the easy-to-identify baryonic constituents of the low-redshift universe represent ≤05 per cent of the total baryon budget. Fukugita et al. (1998) suggested that hot gas in the haloes of galaxies and in groups of galaxies might help solve this 'missing baryons problem'. An additional component of the baryon budget was suggested by numerical cosmological simulations, in which Ω₂ is an initial condition. Such efforts (e.g. Cen & Ostriker 1999; Davé et al. 2001) pointed out that the mass scale of structures in the universe grows with time, and gas falling into these structures at low redshift might then be heated to quite high temperatures. These works suggested that a significant fraction of the low-redshift baryons might then be found in a 'warm-hot intergalactic medium' (WHIM) at temperatures T ≈ 10^7 K and densities peaked at ~10 times the mean density (e.g. Cen & Ostriker 2006). A comparison of a range of models suggests the WHIM is a robust prediction of modern simulations, which predict 30–50 per cent of the low-redshift baryons might be found in this phase of the IGM (Davé et al. 2001; Cen & Ostriker 2006). More recent numerical and analytical works have supported this general conclusion while exploring the effects of feedback (e.g. from galactic winds), non-equilibrium (NEQ) ionization and cooling on these predictions and their connection to observables (e.g. Cen et al. 2001; Fang & Bryan 2001; Phillips, Ostriker & Cen 2001; Furlanetto et al. 2005; Kang et al. 2005; Cen & Ostriker 2006; Cen & Fang 2006; Oppenheimer & Davé 2009).

Given the low densities and high temperatures predicted for the WHIM, the gas in this phase is difficult to detect in emission or absorption. One approach to studying the baryon content of the WHIM is to identify broad Lyα absorption in the low-ż IGM. Tripp et al. (2001), Richter et al. (2004), Sembach et al. (2004) and Lehner et al. (2007) report on the detection of broad Lyα absorbers (BLAs) having b ≥ 40 km s⁻¹, which corresponds to T ≥ 10⁷ K if thermal broadening predominates. Lehner et al. (2007) conclude the fraction of LAF clouds categorized as BLAs is higher at low z than at larger redshifts (from the sample of Kirkman & Tytler 1997), consistent with predictions of cosmological simulations if thermal motions dominate the broadening (see Davé et al. 2001). Some of the BLAs may be blends of narrow lines [or even small ripples in the observed quasi-stellar object (QSO) continuum], a contamination that is difficult to assess with the generally low signal-to-noise ratio (S/N) data available with Space Telescope Imaging Spectrograph (STIS) observations. In one case, Richter et al. (2004) find O VI absorption associated with a BLA for which the ratio of O VI to H I b-values is consistent with pure thermal broadening, strongly suggesting an origin within hot gas at T ≈ 3 × 10⁷ K and supporting the idea that some BLAs are thermally broadened. Similarly, Tripp et al. (2001) identified a blended, broad Lyα line with associated O VI absorption; a joint analysis assuming the H I and O VI arise from the same gas yields T ~ 2 × 10⁷ K.

In addition to broad H I absorption, absorption lines from highly ionized metals may be useful for probing WHIM gas at T ≥ 10⁸ K in filaments or groups (e.g. Verner, Tytler & Barthel 1994b; Mulchaey et al. 1996; Cen & Ostriker 1999). The highly ionized stages of oxygen, the most abundant metal, are the best studied, including O VI and O VII and O VIII. O VII and O VIII have transitions accessible to X-ray instruments, as does O VI. Searches for such absorbers have been hampered by the relatively poor resolution of modern X-ray instruments and the small number of sources observable at high enough S/N by the Chandra and XMM–Newton observatories (see recent summaries by Bregman 2007 and Richter, Paerels & Kaastra 2008). While a number of measurements have been presented in the literature (e.g. Nicastro et al. 2005), some results are questioned by other analyses (Kaastra et al. 2006; Rasmussen et al. 2007) while a few may be on firmer ground (e.g. Fang, Canizares & Yao 2007). It is thus far difficult to judge the fidelity of the X-ray measurements.

Given the high resolution and sensitivity of the currently available ultraviolet spectrographs, searches for absorption due to the O VI 1031, 1037 Å doublet may represent the most efficient means of probing the WHIM, even though O VI is not the dominant ionization state of oxygen for the temperature at which the majority of the WHIM is thought to exist (~10⁸K; Davé et al. 2001). The first blind search for low-redshift O VI absorbers (mostly over 0.6 ≤ z ≤ 1.3) of Burles & Tytler (1996) was only sensitive to very strong absorbers but none the less demonstrated that these absorbers could trace a significant component of the baryonic mass in the universe. Tripp and collaborators first identified a number of O VI absorption-line systems at very low redshift (z < 0.3) with the Far Ultraviolet Spectroscopic Explorer (FUSE) and the STIS on board the Hubble Space Telescope (HST); though their statistical sample was small, these observations suggested a large number density of O VI absorbers at low z (Tripp, Savage & Jenkins 2000; Tripp & Savage 2000). Recent surveys of O VI absorption at low redshift using a complete sample of STIS observations continue to find a very large population of absorbers (Tripp et al. 2008; Thom & Chen 2008a; Danforth & Shull 2008). The number density of intervening O VI absorbers per unit redshift is dN/ dz > 10–20 for equivalent widths W_r(λ1031) > 30 mÅ, perhaps increasing to dN/ dz > 40 for W_r(λ1031) > 10 mÅ (Danforth & Shull 2008). For comparison, recent estimates for the number density of H I absorbers at z < 0.4 give dN_H/I/ dz > 95 for W_r(λ1215) > 90 mÅ (Lehner et al. 2007) and ≈ 130 for W_r(λ1215) > 30 mÅ (Danforth & Shull 2008). The large number of absorbers by itself suggests that the gas probed by these O VI transitions could indeed be an important reservoir of baryons, although accurate estimates of the ionization state and metallicity of these absorbers are required for a quantitative measure of the total mass density.

However, it is possible or even likely that a significant fraction of O VI absorbers do not trace the WHIM, but rather probe metal-enriched, photoionized IGM material. This point has been emphasized in a number of analyses of individual absorbers and sight lines (Savage et al. 2002; Prochaska et al. 2004; Lehner et al. 2006; Tripp et al. 2006; Cooksey et al. 2008), as well as in recent surveys (Tripp et al. 2008; Thom & Chen 2008b). Oppenheimer & Davé (2009) have recently presented cosmological simulations in which O VI absorbers predominantly trace gas at temperatures log T ≈ 4.2, well below the majority of the gas associated with the WHIM. A significant amount of the most commonly used probe of WHIM gas, O VI, may therefore arise in photoionized gas, although Kang et al. (2005) and Oppenheimer & Davé (2009) have argued...
that some of the photoionized O VI may be WHIM gas that has cooled to low temperatures. It remains to be seen, however, if the relatively extreme predictions of Oppenheimer & Davé (2009) will be verified by other simulations.

Undoubtedly, some O VI systems are associated with photoionized gas, though whether they outnumber or dominate the WHIM absorbers is a question open to debate (e.g. Danforth 2009). Even if photoionized absorbers represent a significant fraction of the total, most simulations suggest that the highest equivalent width O VI systems are most likely to be collisionally ionized, tracing either WHIM gas or gas associated with the hot haloes of galaxies (Cen et al. 2001; Fang & Bryan 2001; Ganguly et al. 2008; Oppenheimer & Davé 2009).

While O VI may not be a perfect tracer of the WHIM, and X-ray measurements are not yet secure, observations of EUV transitions that are redshifted into the bands of FUSE and HST provide other evidence for shock-heated hot gas in the low-z IGM. In particular, the doubllets of Ne VIII λλ 737.409, 780.324, Mg x λλ 690.790, 624.950 and Si XII λ λ 4.994.406, 520.665 are potentially useful probes of hot gas in redshifted IGM (e.g. Verner et al. 1994Ab) or intragroup (Mulchaey et al. 1996) material; these ions peak in abundance in collisional ionization equilibrium (CIE) at temperatures of T ≥ 6 × 10^5 K, 1.2 × 10^6 and 2 × 10^6 K, respectively (Gnat & Sternberg 2007). Given the large energies required to produce these ions, they should represent good probes of hot, collisionally ionized gas. They probe temperatures in the same range as X-ray absorption lines, but at better sensitivity to a given H column density given the maturity of the ultraviolet (UV) instruments with which they can be detected. Savage et al. (2005) have reported on a detection of intervening Ne VIII at z ≈ 0.21 that they show comes from hot gas. The Ne vuv-bearing gas is part of a multiphase2 absorber with strong O VI in addition to complex low-ion absorption. The ratio of integrated column densities in this absorber is N(NE VIII)/N(O VI) = 3.3 ± 0.10, which is consistent with gas in CIE near T ≈ 5 × 10^5 K. Searches for Ne VIII absorption associated with 10 other O VI absorbers have thus far yielded no further detections (Prochaska et al. 2004; Richter et al. 2004; Lehner et al. 2006). However, most of the O VI absorbers are much weaker than that discussed by Savage et al., and in only three of these non-detections is the limit N(NE VIII)/N(O VI) < 0.5. Thus, Ne VIII has not yet been the subject of a comprehensive search [see limits on d/V/dz in Prochaska et al. (2004)]. To date, however, most Ne VIII searches have used O VI-based searches; if the two ions do not coexist because the WHIM is quite hot, this may not be the best approach.

Here, we present a detailed analysis of the ionization state and chemical abundances of the strong O VI absorber at z = 0.495 096 towards PKS 0405-123. The system was identified previously by Bahcall et al. (1993) in Lyα absorption using the Faint Object Spectrograph on board HST. Aspects of this absorber have previously been discussed by Prochaska et al. (2004), Williger et al. (2006), Lehner et al. (2006), Tripp et al. (2008) and Thom & Chen (2008a,b) based on FUSE and HST observations. This absorber exhibits numerous metal-line absorption features in high-resolution spectra obtained using FUSE and STIS, as previously mentioned by Prochaska et al. (2004). The large spectral coverage of the combined FUSE and STIS spectra provides access to ~15 ions, including six oxygen ions (O VI through O IV), and the highly ionized tracers of hot gas Ne VIII and Mg x. Coverage of the large number of ionization states of oxygen and other elements gives us the opportunity to study in detail the ionization mechanisms that may be at work in this gas and place constraints on the temperature of the absorbing material. This absorber is among the strongest 5 to 10 per cent of all O VI systems, and the simulations predict strong absorbers like this are more likely to be associated with hot, collisionally ionized material. The results of our analysis show that the z ~ 0.495 absorber towards PKS 0405-123 must contain a substantial photoionized component, and may or may not also contain ≥ 2 × 10^6 K gas as part of a multiphase structure. The lack of significant Ne VIII and Mg x places limits on the amount of hot WHIM gas in this system.

We discuss out the observations used here in Section 2. In Section 3, we discuss our measurements of the properties of the absorber. We provide a detailed analysis of the possible ionization mechanisms in this system in Section 4, and discuss the implications in Section 5. Finally, we summarize our principal results in Section 6.

2 OBSERVATIONS

In this work, we present observations of the z = 0.495 absorber towards PKS 0405-123 taken by several UV spectrographs. Our analysis focuses on three spectroscopic data sets at UV wavelengths: (1) far-ultraviolet (FUV) spectra obtained with FUSE covering λ ~ 912–1150 Å (R ~ 15000); (2) STIS/E140M echelle spectroscopy acquired with HST covering λ ~ 1150–1700 Å (R ~ 46000) and (3) Faint Object Spectrograph (FOS)/G190H spectroscopy from HST covering λ ~ 1570–2330 Å (R ~ 1300). We describe each of these data sets briefly below.

2.1 FOS spectroscopy

PKS 0405-123 was observed with the FOS using the G190H grating and the C-2 (0.25 × 2.0 arcsec^2) aperture to feed the ‘blue’ digicon as part of GTO program 1025 (PI: Bahcall). The total exposure time with the FOS was 3.8 ksec. These are pre-COSTAR data and have been described by Bahcall et al. (1993) and Jannuzi et al. (1998), among others. We adopt the reduced data from the uniform FOS reduction of Bechtold et al. (2002)4 who describe their reductions in detail. We use the FOS data to study the Lyα absorption from the z = 0.495 absorber. This absorber is unresolved at the resolution of FOS [R ~ 1300 or Δλ ~ 230 km s^{-1} full width at half-maximum (FWHM)]. The data have a S/N of ~13 per pixel, with four pixels per resolution element.

2.2 STIS spectroscopy

PKS 0405-123 was observed by STIS using the E140M grating and the 0.2 × 0.06 arcsec^2 aperture to feed the FUV MAMA detector as part of the GTO program 7576 (PI: Heap). This setup yields spectra with a velocity resolution ΔV ~ 7 km s^{-1} (FWHM) with approximately two pixels per resolution element. The spectral coverage of the STIS data is λ ~ 1150–1700 Å. The total exposure

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1 Verner et al. (1994b) quote give wavelengths for the Mg x λ 624.950 Å and Si XII λ 520.665 Å transitions that are not in agreement with the wavelengths given in Verner, Barthel & Tytler (1994a). The latter agree with those available via National Institute of Standards and Technology (NIST). We quote the NIST wavelengths throughout for these transitions.

2 The term multiphase will be used here to denote an absorber with a mixture of gas with differing temperatures and ionization states where these differences are often driven by differing ionization mechanisms.

3 Hereafter, we simply refer to this as the z = 0.495 absorber.

4 The data are available at http://lithops.as.arizona.edu/~jill/QuasarSpectra/.
time of the observations is 27.2 ksec. The data have S/N $\approx 5$–7 per pixel. The absolute velocities are accurate to $\sim 0.5$–$1.0$ pixels ($\sim 2$–$4$ km s$^{-1}$) while the relative wavelength scale is twice as good (Kim Quijano et al. 2007), though Tripp et al. (2005) have noted occasional wavelength scale errors in excess of these values.

The STIS data have been discussed extensively in the context of IGM absorption by Chen & Prochaska (2000) and Prochaska et al. (2004), who discuss metal-line absorbers, as well as Williger et al. (2006) and Lehner et al. (2007), who concentrate on the properties of the H I absorption. Our reduction is that used by Lehner et al. (2007). Our measurements of the $z = 0.495$ system will differ slightly from Prochaska et al. given the slightly different reduction, our choice of integration limits, reconsideration of continuum placement and other details.

2.3 FUSE spectroscopy

PKS 0405$-$123 has been observed by FUSE (Moos et al. 2000; Sahnow et al. 2000) as part of GI programs B087 (PI: Prochaska) and D103 (PI: Howk) for a total exposure time of 142 ksec. Prochaska et al. (2004) and Chen & Prochaska (2000) have reported on aspects of the IGM; the data used here approximately double the exposure time of those earlier observations. The FUSE observations were taken in time-tag (TTAG) or photon event mode with the object centred in the LWRS (30 $\times$ 30 arcsec$^2$) apertures. The FUSE data have been uniformly reduced with CaFUSE v3.1 (Dixon et al. 2007). These data have a velocity resolution $\Delta v \sim 20$ km s$^{-1}$ (FWHM) and are binned to 0.027 Å per pixel ($\approx$7–8 km s$^{-1}$ per pixel), giving roughly 3 pixels per resolution element. We have combined the data from all channels in regions of overlap to provide S/N of $\sim$10 per pixel over the spectral range covered by the LiF channels ($\sim 1000$–1180 Å) and S/N $\sim$ 6 per pixel over the range covered by the SiC channels ($\sim 915$–1000 Å). While this coaddition of channels can lead to a slight degradation in the breadth and shape of the line spread function (LSF), the increase in S/N of data outweighs this slight effect.

The absolute wavelength calibration of FUSE is not well determined. We have set the zero-point by comparing absorption lines from the Galactic interstellar medium in the FUSE bandpass with similar lines in the STIS bandpass (e.g. comparing lines of Fe II, Si II and O I between the instruments). This approach generally leads to zero-point uncertainties of the order of $\sim 2$–$5$ km s$^{-1}$, although our experience has shown this can occasionally be as large as 10 km s$^{-1}$.

3 THE $Z = 0.495$ ABSORPTION SYSTEM

The focus of this paper is the $z \approx 0.495$ absorption system towards PKS 0405$-$123 ($z_{em} = 0.574$). Here, we discuss the velocity structure of the absorber and separately describe our analysis of the metals and H I in this system.

Fig. 1 presents the normalized profiles of several important metal ions and Ly$\beta$ (see Section 3.2) for this absorber for an assumed zero-point of $z = 0.495$ 096. The redshift is based on the centroid of the strong C m 977 Å transition. The continua were estimated by fitting low-order Legendre polynomials to regions free of absorption lines following Sembach & Savage (1992). Due to the simplicity of the quasar spectrum, most continua for this work were first-order (linear) fits.

We identify significant metal-line absorption in the C m 977 Å, N iv 765 Å, O iv 787 Å, O v 629 Å and O vi 1031, 1037 Å transitions. The measurement of O v $\lambda$629 is the first direct detection of this ion in intervening absorbers at $z < 1$ (though see Telfer et al. 2002 for an indirect detection of the composite absorption from many LAF clouds). In addition, our data include non-detections of strong lines from C ii, N ii, N iii, O ii, O iii, Ne viii and Mg x, among others. We do not show profiles for all the ions covered by our data, as the upper limits for several are not particularly stringent or important in our final analysis.

3.1 Metal ion absorption

3.1.1 Apparent column densities and velocity profiles

Our measurements of the properties of the $z \approx 0.495$ absorption-line system are presented in Table 1, including our assumed atomic data (taken from the compilations of Verner et al. (1994a) and

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The columns integrated over the profiles are given, derived using a combination of the apparent optical depth (AOD) method of Savage & Sembach (1991) and profile fitting techniques (described below). The AOD, \( \tau_a \), of an absorption profile is written as \( \tau_a = -\ln \left( I(0)/I_a(\lambda) \right) \), where \( I(0) \) and \( I_a(\lambda) \) are the observed intensity across the profile and the estimated continuum intensity, respectively. The apparent column density, \( N_a(\lambda) \), is then \( N_a(\lambda) = (m_e) \int \frac{N(\lambda,v)}{\lambda^2} dv \). In the absence of unresolved saturation, the apparent column density is a valid, instrumentally blurred representation of the true column density distribution. Those regions of the profile exhibiting unresolved saturated structure will be lower limits to the true column density. The integration of the \( N_a(\lambda) \) profile is the total apparent column density, which is reported in Table 1, along with the equivalent widths of the absorption. All of the upper limits are \( 3\sigma \) following Wakker et al. (1996). The O\( \text{\textsc{vi}} \) absorption deserves some discussion, which we postpone to Section 3.1.3. The column for C\( \text{\textsc{iii}} \) is derived from profile fits to the data for this ion (see below). The \( N_a(\lambda) \) integration, which is not as reliable as the profile fits for this ion, gives log \( N(\text{C\textsc{iii}}) > 13.31 \).

We show the \( N_a(\lambda) \) profiles of several ions in Fig. 2. With Fig. 1, these figures show the gas in this system can be broken into three main absorption blends centred at \( v \sim -30 \), 0 and \( +50 \) km s\(^{-1} \), which we refer to as components 1, 2 and 3, respectively. These components are most prominently viewed in the profiles for C\( \text{\textsc{iii}} \), O\( \text{\textsc{iv}} \) and O\( \text{\textsc{vi}} \).

### Table 1. Integrated equivalent widths and column densities.

<table>
<thead>
<tr>
<th>Ion</th>
<th>IP (eV)(^b)</th>
<th>( \lambda_0 ) (Å)</th>
<th>( f )(^c)</th>
<th>( W_\tau ) (mÅ)</th>
<th>log ( N_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H( \text{\textsc{i}} )</td>
<td>0–13.6</td>
<td>1215.670</td>
<td>0.4162</td>
<td>540 ± 80</td>
<td>14.07 ± 0.06(^d)</td>
</tr>
<tr>
<td>H( \text{\textsc{ii}} )</td>
<td>0–13.6</td>
<td>1025.722</td>
<td>0.0791</td>
<td>90 ± 19</td>
<td>14.22 ± 0.09(^d)</td>
</tr>
<tr>
<td>H( \text{\textsc{iii}} )</td>
<td>0–13.6</td>
<td>972.537</td>
<td>0.0290</td>
<td>&lt;50</td>
<td>&lt;14.31(^e)</td>
</tr>
<tr>
<td>C( \text{\textsc{ii}} )</td>
<td>11.3–24.4</td>
<td>903.962</td>
<td>0.336</td>
<td>&lt;32</td>
<td>&lt;13.12</td>
</tr>
<tr>
<td>C( \text{\textsc{iii}} )</td>
<td>24.4–47.9</td>
<td>977.020</td>
<td>0.757</td>
<td>89 ± 9</td>
<td>13.39 ± 0.05(^e)</td>
</tr>
<tr>
<td>N( \text{\textsc{ii}} )</td>
<td>14.5–29.6</td>
<td>1083.990</td>
<td>0.111</td>
<td>&lt;54</td>
<td>&lt;13.68</td>
</tr>
<tr>
<td>N( \text{\textsc{iii}} )</td>
<td>29.6–47.4</td>
<td>989.799</td>
<td>0.123</td>
<td>&lt;38</td>
<td>&lt;13.55</td>
</tr>
<tr>
<td>N( \text{\textsc{iv}} )</td>
<td>47.4–77.5</td>
<td>765.148</td>
<td>0.616</td>
<td>29 ± 9</td>
<td>13.01 ± 0.16</td>
</tr>
<tr>
<td>O( \text{\textsc{ii}} )</td>
<td>13.6–35.1</td>
<td>834.465</td>
<td>0.132</td>
<td>&lt;40</td>
<td>&lt;13.68</td>
</tr>
<tr>
<td>O( \text{\textsc{iii}} )</td>
<td>35.1–54.9</td>
<td>832.927</td>
<td>0.107</td>
<td>&lt;36</td>
<td>&lt;13.73</td>
</tr>
<tr>
<td>O( \text{\textsc{iv}} )</td>
<td>54.9–77.4</td>
<td>787.711</td>
<td>0.111</td>
<td>106 ± 8</td>
<td>≥14.37(^f)</td>
</tr>
<tr>
<td>O( \text{\textsc{v}} )</td>
<td>77.4–113.9</td>
<td>629.730</td>
<td>0.515</td>
<td>218 ± 8</td>
<td>&gt;14.39</td>
</tr>
<tr>
<td>O( \text{\textsc{vi}} )</td>
<td>113.9–138.1</td>
<td>1031.926</td>
<td>0.1325</td>
<td>215 ± 9</td>
<td>14.47 ± 0.02(^g)</td>
</tr>
<tr>
<td>O( \text{\textsc{vii}} )</td>
<td>113.9–138.1</td>
<td>1037.617</td>
<td>0.0658</td>
<td>95 ± 13</td>
<td>14.50 ± 0.05(^g)</td>
</tr>
<tr>
<td>Ne( \text{\textsc{viii}} )</td>
<td>207.3–239.1</td>
<td>770.409</td>
<td>0.1030</td>
<td>&lt;29</td>
<td>&lt;13.73</td>
</tr>
<tr>
<td>Ne( \text{\textsc{vii}} )</td>
<td>207.3–239.1</td>
<td>780.324</td>
<td>0.0505</td>
<td>&lt;25</td>
<td>&lt;13.97</td>
</tr>
<tr>
<td>Mg( \text{\textsc{x}} )</td>
<td>367.5–367.5</td>
<td>624.950</td>
<td>0.041</td>
<td>&lt;44</td>
<td>&lt;14.49</td>
</tr>
<tr>
<td>S( \text{\textsc{v}} )</td>
<td>72.6–88.1</td>
<td>933.378</td>
<td>0.437</td>
<td>&lt;23</td>
<td>&lt;12.83</td>
</tr>
</tbody>
</table>

\(^a\)All upper limits are 3\( \sigma \). Ions with rest wavelengths \( \lambda_0 > 880 \) Å are from STIS observations, with \( \lambda_0 < 880 \) Å from FUSE observations.

\(^b\)The range of creation and ionization energies for each species (Däppen 2000).

\(^c\)Atomic oscillator strengths from Morton (2003) for \( \lambda_0 > 912 \) Å and Verner et al. (1994a) for \( \lambda_0 < 912 \) Å.

\(^d\)We adopt a total H\( \text{\textsc{i}} \) column density of log \( N(H\text{\textsc{i}}) = 14.29 ± 0.10 \) based on a combined profile-fitting analysis of the three transitions reported in this table. The integrations here cover the entire breadth of the profile.

\(^e\)Adopted from a component-fitting analysis.

\(^f\)Column density lower limit from a straight integration of the apparent column density. A component-fitting analysis gives 14.50 ± 0.08, but it is sensitive to the assumed properties of the FUSE LSF (see text).

\(^g\)We adopt a total O\( \text{\textsc{vii}} \) column density of log \( N(O\text{\textsc{vii}}) = 14.47 ± 0.02 \) based on a weighted mean of the two lines, including absorption from the discrepant areas. The amount of O\( \text{\textsc{vi}} \) associated with components 1, 2 and 3 is log \( N(O\text{\textsc{vi}}) = 14.41 ± 0.05 \) (see Section 3.1.3). This is the value used in our modelling.

3.1.2 Profile fitting of metal lines

The O\( \text{\textsc{iv}} \) and C\( \text{\textsc{iii}} \) profiles show quite strong absorption in the central component 2 (\( v \sim 0 \) km s\(^{-1} \)), with peak AODs of \( \tau_a \approx 1.4 \) and 1.7, respectively. Such large AODs suggest there may be some unresolved saturated structure in the profiles, making the measured apparent column densities lower limits to the true columns. An alternate way to derive the column densities is to fit an instrumentally smoothed model to the absorption profiles of these species. We use the profile fitting software of Fitzpatrick & Spitzer (1997) for this purpose. The parameters for the fit are the central velocity, Doppler parameter (\( b \)-value) and column density of each assumed component or cloud. The approach assumes each component can be described by a Maxwellian velocity distribution.

The fits depend on the adoption of an instrumental LSF. For the STIS observations of C\( \text{\textsc{iii}} \) \( \lambda 977 \), we adopt the STIS E140M LSF from Kim Quijano et al. (2007). For the FUSE observations of O\( \text{\textsc{iv}} \) \( \lambda 787 \), we adopt a Gaussian LSF with a FWHM of 20 km s\(^{-1} \). The true breadth and shape of the FUSE LSF are uncertain (see below).

The C\( \text{\textsc{iii}} \) and O\( \text{\textsc{iv}} \) profiles were both well fit by a three-component model, mirroring our discussion of the component structure above, with reduced \( \chi^2 \) values very near unity. The precise \( \chi^2 \) values are sensitive to the range over which they are calculated, mostly driven by the presence of large noise excursions (e.g. near \( v \sim -47 \) km s\(^{-1} \) in the C\( \text{\textsc{iii}} \) profile; see Fig. 1). The results of the profile
components in the O profile due to the change in the fitted width of the original data.

The STIS observations (transitions with \( \lambda_0 > 790 \, \text{Å} \)) are binned by a factor of 2 to approximately one datum per resolution element (\( \sim 7 \, \text{km s}^{-1} \)). The FUSE data have approximately the same pixel spacing, with three pixels per 20 km s\(^{-1}\) resolution element.

Fitting for these transitions, which we fit independently, are given in Table 2. Comparing the total columns derived in this way with the \( N_a(\nu) \) integrations (see previous subsection) suggests significant corrections to the apparent columns due to saturation effects are required. Fig. 3 shows the component models for each fit with the original data.

The \( \text{O}^\text{IV} \) results are derived from a fit of the FUSE data. This line is observed by both FUSE and STIS, although the STIS data have very low S/N (see e.g. Williger et al. 2006). We have tested the effects of simultaneously fitting the FUSE and STIS data and find no differences in the results. This is not surprising: because the fits are weighted by the variance of the data, the low S/N of the STIS data ensures they do not contribute to the fits nearly as much as the FUSE data. However, the column density of \( \text{O}^\text{IV} \) can be sensitive to the adopted width of the FUSE LSF, whose shape is poorly constrained, due to the change in the fitted \( b \)-value. Furthermore, additional components in the \( \text{O}^\text{IV} \) profile can cause significant increases in the column density and are not well constrained on the whole. A \( \pm 10 \) per cent change in the FWHM of the assumed LSF leads to changes in the total \( \text{O}^\text{IV} \) column of \( -0.06 \) and \( +0.10 \) dex. As the LSF breadth is increased, the errors in the determination become quite large due to the increasing dependence on the \( b \)-value with increasing saturation of the model. (For an LSF with FWHM \( \approx 22 \, \text{km s}^{-1} \), the uncertainties are nearly an order of magnitude.) Given these uncertainties, we will proceed by adopting the lower limit to the \( \text{O}^\text{IV} \) column from the \( N_a(\nu) \) integration discussed above.

The STIS observations of \( \text{C}^\text{III} \) profile are good measures of the true column. In what follows, we adopt the profile fitting results for \( \text{C}^\text{III} \), as noted in Table 1.

### 3.1.3 The \( \text{O}^\text{VI} \) absorption

The \( N_a(\nu) \) profiles of the weak and strong transitions of \( \text{O}^\text{VI} \) at 1031.926 and 1037.617 Å, respectively, are shown in Fig. 4. For velocities \( v \lesssim +20 \, \text{km s}^{-1} \), these transitions are in good agreement. However, they do not agree with one another or the other metal

![Figure 2](image-url). Apparent column density profiles of metal ions in the \( z = 0.495096 \) absorber towards PKS 0405–123. Both \( \text{O}^\text{VI} \) lines are shown given the differences between them (see Section 3.1.3), which is shown by the dashed regions. The profile for \( \text{C}^\text{III} \) is shown in each panel, multiplied by a factor of 10 to match the scale of the other ions. There is good agreement in the component structure between most of the ions. The thin dashed vertical lines show the locations of the components fit to the \( \text{C}^\text{III} \) profile (see Section 3.1.2 and Fig. 3). The STIS observations (transitions with \( \lambda_0 > 790 \, \text{Å} \)) are binned by a factor of 2 to approximately one datum per resolution element (\( \sim 7 \, \text{km s}^{-1} \)). The FUSE data have approximately the same pixel spacing, with three pixels per 20 km s\(^{-1}\) resolution element.

![Figure 3](image-url). The normalized absorption profiles of \( \text{C}^\text{III} \lambda 977 \) and \( \text{O}^\text{IV} \lambda 787 \) with the adopted profile fits overlaid, assuming a redshift of \( z = 0.495096 \).

The properties of the three components used in these fits are summarized in Table 2. The velocity centroids are shown by thick black ticks above each spectrum (see the text for details of the fitting procedure).

### Table 2. Component fitting results.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Component</th>
<th>( v_c ) (km s(^{-1}))( ^a )</th>
<th>( \log N )</th>
<th>( b ) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{C}^\text{III} )</td>
<td>1</td>
<td>( -26.7 \pm 1.8 )</td>
<td>12.56 ( \pm 0.15 )</td>
<td>( \ldots )( ^d )</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>( 0.0 \pm 1.0 )</td>
<td>13.20 ( \pm 0.06 )</td>
<td>8.5 ( \pm 1.5 )</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>( +50.7 \pm 2.1 )</td>
<td>12.70 ( \pm 0.10 )</td>
<td>8.9 ( \pm 3.8 )</td>
</tr>
<tr>
<td>( \text{O}^\text{IV} )</td>
<td>1</td>
<td>( -33.3 \pm 2.1 )</td>
<td>13.90 ( \pm 0.08 )</td>
<td>7.8 ( \pm 5.6 )</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>( +1.5 \pm 1.3 )</td>
<td>14.31 ( \pm 0.11 )</td>
<td>9.1 ( \pm 2.9 )</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>( +51 \pm 3 )</td>
<td>13.47 ( \pm 0.11 )</td>
<td>( \ldots )( ^d )</td>
</tr>
</tbody>
</table>

\( ^a \) Central velocity relative to \( z = 0.495096 \).

\( ^b \) Our adopted redshift is defined by the central velocity of this component.

\( ^c \) Given the low resolution of FUSE and the behaviour of the profile fitting for this component, the quoted column density should be considered a lower limit.

\( ^d \) The \( b \)-value of this component is held fixed in the fitting to avoid fitting an unreasonably low value. The absorption is weak enough that the column density is not very sensitive to the adopted \( b \)-value.
placed significantly between the visits. The data extracted for the two visits individually are consistent over these wavelength regions, which would not be the case for hot pixels fixed on the detector. Thus, this explanation is not tenable.

We have attempted to simultaneously fit the profiles of the O\textsc{vi} doublet as observed by STIS. Aside from the velocity range of possible contamination, the \( N_v(v) \) profiles of the 1031 and 1037 Å transitions seen in Fig. 4 are in good agreement, implying the effects of unresolved saturation cannot be large (as also evidenced by the agreement in integrated apparent columns; see Table 1). The fitting was undertaken to attempt to disentangle the component structure of the absorption and to provide a measure of the column density of the higher velocity components, especially component 3 (\( v \approx +50 \text{ km s}^{-1} \)), which is strongly blended with the contaminated or compromised regions. We attempted fits under two assumptions: (1) the discrepant regions in the O\textsc{vi} lines are contaminated by interloping absorbers and (2) the discrepant regions suffer from difficulties in the wavelength assignment, but represent O\textsc{vi} absorption associated with this absorber.

In the first of these fits, we artificially increased the variance over the velocity ranges \(+23 \leq v \leq +53 \text{ km s}^{-1}\) and \(+19 \leq v \leq +43 \text{ km s}^{-1}\) for the 1031 and 1037 Å transitions, respectively, to such large values that they do not affect the calculation of \( \chi^2 \) and, hence, the parameters of the fit. The fits to the regions encompassed by components 1 and 2 are non-unique, and can be fit with one, two or three components with similar values of \( \chi^2 \). Part of the difficulty in fitting these lower-velocity components is the loss of information on the positive velocity side of the profiles due to the assumed contaminating absorption. In addition, the component structure in the O\textsc{vi} profiles is not distinct. This is in contrast to the C\textsc{iii} and O\textsc{iv} profiles in this region. If the component structure is assumed to follow that of C\textsc{iii}, with velocities fixed to those in Table 2, the total column density for this model is \( \log N(\text{O vi}) = 14.41 \pm 0.05 \).

The fit is shown in Fig. 5 as the thick grey line, with the central velocities of the components shown above the profiles. A fit in which velocities of the O\textsc{vi} components are free parameters is also shown as the thick dashed black line (the black ticks above the profiles show the central velocities in this case). The total column density is \( \log N(\text{O vi}) = 14.40 \pm 0.16 \). In this fit, the largest column density is in component 1; the large fitted \( b \)-value for this component has a significant uncertainty, which is the source of the much larger error in this model than with the velocities fixed to the C\textsc{iii} solution. Both fits have indistinguishable values of \( \chi^2 \). In each case, the columns of component 3 are very nearly the same near \( z \sim 0.5 \text{ O vi absorption} \)

\begin{align*}
\text{Figure 4. Apparent column density profiles of the O\textsc{vi} transition from the} \\
\text{\( z = 0.495 \) absorber towards PKS 0405–123. The top two} \\
\text{panels show the strong and weak lines, at 1031, 926 and 1037, 617 Å, respectively, at full} \\
\text{sampling. The bottom panel shows both \( N_v(v) \) profiles binned by two pixels} \\
\text{to one pixel per resolution element). At velocities \( 15 \leq v \leq 45 \text{ km s}^{-1} \), the} \\
\text{discrepancies in the two profiles may be caused by intervening transitions, presumably \textit{Ly}α.}
\end{align*}
discrepant region in OVI that does not appear in CIII and OIV. Because the discrepant component is not seen in CIII or OIV, it must have significantly different ionization conditions than the rest of the gas, and we do not attempt to model it. Because most of our models will assume a solar C/O ratio, metallicities [C/H] derived from CIII will also imply a given [O/H]. Thus, for our ionization and metallicities.

Figure 5. The normalized absorption profiles of OVI λ1031 and 1037 with profile fits overlaid. The top two panels show the profiles assuming the OVI lines are contaminated with interloping absorbers (thin dashed lines denote regions of the data we assume to be contaminated). Two fits are shown in these panels: one assuming a three-component fit with velocities fixed to those found in CIII and the other allowing the velocities of the OVI components to be a free parameter. The reduced $\chi^2$ values are indistinguishable for these two models. The bottom two panels show our fits assuming there is no contamination of the profiles. The $\chi^2$ is significantly worse in this case. (However, the contribution to the $\chi^2$ values for the range of data assumed to be contaminated in the upper panels is minimized by artificially increasing the variance of the data over those ranges.) The total column density for the models in the upper panels is consistent with log $N$(OVI) = 14.40 (albeit with much different errors; see text) whereas the bottom panels give log $N$(OVI) = 14.50 ± 0.13. The discrepancy is due to the lower equivalent width attributed to OVI in the upper panels.

above, this gives a total column density of log $N$(OVI) = 14.38 ± 0.05 excluding the compromised regions (i.e. for components 1 to 3). Thus, the uncertainty derived using a model with temperatures fixed to those found in CIII provides an uncertainty closer to the $N_a(v)$-derived values. We note that including absorption associated with component 3 only impacts the metallicities – the ratios of OVI/CIII and OIV/CIII derived for components 1 and 2 are consistent with the ratio after including component 3, which adds $\sim +0.1$ dex to these three ions. Thus, had we chosen to model the clearly uncompromised velocity range, we would derive the same results as those presented below.

3.1.4 Limits on the multiphase structure from velocity profiles

The $N_a(v)$ profiles shown in Fig. 2 demonstrate that the ions CIII, OIV, OVI and OVI in this absorber have a similar velocity structure, with gas associated with the three components discussed above (and perhaps a fourth seen in OVI and OVI). The profile fitting results of Section 3.1.2 reinforce this basic structure, though with the caveat that the limited resolution of the data could be hiding substructure within the components (or component blends) identified in Table 2. The H1 and metal ions would be considered ‘well-aligned’ in the categorization of Tripp et al. (2008) since their central velocities are consistent with one another within 2σ. However, the uncertainties in the H1 centroid are relatively large, so the meaning of this alignment is not clear. In addition, too little information is available for Lyman-series absorption to know if the detailed component structure hinted at in the metal ions is mirrored in H1.

While the metal-line profiles in Fig. 2 are generally similar, there are hints of differences between them. The broad envelope of the OVI distribution (at $v \lesssim +20$ km s$^{-1}$) is similar to the OIV and CIII distributions, and the total velocity extents of OVI, OIV and CIII are all very similar (including the gas in component 3 at $v \approx +50$ km s$^{-1}$). However, OVI seems less prominent over the velocity range of component 2 compared with the lower-ionization species. This may be due to changing ionization conditions between components 1 and 2, with a corresponding change in the ion ratios, or due to somewhat broader components in OVI. These differences, however, are at the limits of the noise and resolution of the current data. It is difficult to say whether or not they are significant. If so, they may imply the existence of a warmer phase of the gas traced by OVI and a cooler phase traced by CIII and OIV. However, if this is true, both phases must be present at the same velocities.

The component Doppler parameters given in Table 2 limit the temperature of the gas. For example, the $b$-values of CIII and OIV for component 2 imply maximum temperatures of $T \lesssim (5.2 \pm 1.8) \times 10^4$ K and $\lesssim (8 \pm 5) \times 10^4$ K, respectively. The contribution of a hot component to these species must not produce absorption profiles broader than observed. To test whether a significant amount of warm-hot gas (with $T > 10^5$ K) could be included in these profiles, we have fit the CIII and OIV profiles including an additional component forced to have a $b$-value appropriate for gas with $T \gtrsim 10^5$ K. For CIII, we find that any broad components added in this way must have negligible column densities in order to be consistent with the observed profiles. This is not unexpected given the small ionization fraction of CIII in gas with such temperatures (see below). For OIV, one can include a broader component centred

5 The profile fits OIV are uncertain as discussed above. Lowering the FWHM of the assumed LSF for FUSE to 18 km s$^{-1}$ allows for temperatures $\lesssim (1.0 \pm 0.5) \times 10^6$ K.
near $\approx 0\text{ km s}^{-1}$. Adopting a $b$-value of 10 km s$^{-1}$, corresponding to $T \lesssim 10^5$ K for such a component, leads to very small column densities in that component or forces the existing component 2 to have unphysically low $b$-values (implying temperatures much lower than expected for the IGM) for reasonable values of $\chi^2$. If one assumes $b = 16$ km s$^{-1}$, corresponding to $T \lesssim 2.5 \times 10^4$ K, the fits are significantly better. Our fits suggest at the most 30 per cent of the total column of O VI can come from such a component. This limit comes about because as the column of the broad component is increased above $\log N$(O IV) $\approx 13.7$, the column of the existing component 2 increases as well (due to a decreasing $b$-value for component 2). This conclusion is robust to changes in the adopted LSF for FUSE. It is mostly driven by the nature of a multicomponent curve of growth, where the $b$-value of the narrow component is decreased in order to account for an increased contribution to the equivalent width from the broad component. The decrease in the $b$-value for the narrow component increases the total column density substantially, always keeping the broad component to $\lesssim 30$ per cent of the total.

Thus, given the profile comparisons and the profile fitting results, there may be room, if not some evidence, for a multiphase structure within this absorber. The discrepancies between the $N_c(v)$ profiles of the ions that might imply a multiphase structure are subtle compared with those seen in many absorbers (e.g. Tripp et al. 2008), and the O VI and other ions are reasonably well aligned with the H I in this system (see Fig. 1). If broad, warm-hot ($T \gtrsim 10^5$ K) gas is present, it can only contribute $\lesssim 30$ per cent of the total column of O IV and must have a negligible contribution to the C III column density. In such a scenario, O VI may preferentially trace the warm-hot material, C III would trace the cooler gas (at $T \lesssim 5 \times 10^4$ K) and O IV would include contributions from both, albeit with a larger contribution from the cooler mater. The warm-hot gas traced by O VI in such a scenario cannot be too hot ($T \lesssim 3 \times 10^5$ K) in order to avoid producing too much Ne VIII or too little O V (see Section 4).

### 3.2 H I Lyman-series absorption

Fig. 6 shows the normalized absorption-line profiles from the Lyα, Lyβ and Lyγ transitions of neutral hydrogen for the $z = 0.495$ absorber. The Lyα observations are taken from the low-resolution FOS data ($\approx 230\text{ km s}^{-1}$ FWHM), while the Lyβ and Lyγ are from the high-resolution STIS data ($\approx 7\text{ km s}^{-1}$ FWHM). The Lyα transition is poorly resolved by the FOS, the Lyβ line is poorly detected by STIS and Lyγ is undetected. We therefore have very little information on the velocity structure of the H I in this system.

Table 1 reports our integrated rest-frame equivalent widths and limits for these transitions. The Lyα line integration is over the range $\pm 350$ km s$^{-1}$, while the integration for Lyβ and Lyγ is over $\pm 85$ km s$^{-1}$. To better constrain the H I column in the face of the resolution and detection limitations, we have performed a simultaneous profile fit to these three transitions as described above (see also the appendix given in Lehner et al. 2007 for this absorber). We adopt a Gaussian LSF for the FOS data and allow for a shift in the FOS data relative to the STIS data given the better absolute wavelength calibration of the latter.

The results of the fit are shown in Fig. 6 as the smooth solid lines. We note that the results of the fit are somewhat sensitive to the range over which one calculates the $\chi^2$ goodness of fit parameter. We have investigated the range of column densities implied as one varies these limits, incorporating an estimate of this variability into our error estimate. From this analysis, we adopt a best-fitting column density of $\log N$(H I) $= 14.29 \pm 0.10$. This yields a $b$-value of $b = 68 \pm 8$ km s$^{-1}$ for a single-component fit to the profiles with a central velocity of $v_c = +9 \pm 8$ km s$^{-1}$ relative to $z = 0.495096$ (from C III).

Our adopted H I column is comparable to the values derived from earlier studies that include this absorber: $\log N$(H I) $= 14.31 \pm 0.07$ (Tripp et al. 2008), 14.3 $\pm$ 0.1 (Thom & Chen 2008b), 14.39 $\pm$ 0.07 (Williger et al. 2006) and $>$13.95 (Bahcall et al. 1993; using their Lyα equivalent width). The central velocity is driven by the Lyβ detection shown in Fig. 6; obviously there is significant uncertainty in this determination given the poor quality of that profile. While the derived velocity is within $\sim 1 \sigma$ of the central value of C III, O VI and other ions, the poor quality of the H I determination limits our ability to draw significant conclusions from this alignment. As discussed above, the H I would be described as ‘well-aligned’ under the Tripp et al. (2008) definition since the central velocities of H I and O VI are within 2σ of one another. The $b$-value provides a firm limit to the weighted mean temperature of the H I-bearing gas of $T \lesssim (2.8 \pm 0.7) \times 10^4$ K assuming pure thermal broadening. The $b$-value assumes a single component describes the H I broadening, though our data are not of high enough quality to determine if the H I component structure follows that of the metals (with multiple components).

### 4 Ionization of the Absorber

Given the importance of O VI as a tracer of shock-heated gas in the low-redshift IGM, the presence of strong O VI in the $z = 0.495$ absorber towards PKS 0405–123 might imply this system is tracing the WHIM at low redshift. However, as emphasized by a number of authors (Savage et al. 2002; Prochaska et al. 2004; Lehner et al. 2006; Tripp et al. 2008; Thom & Chen 2008b), O VI may not be a pure tracer of shock-heated WHIM material. If not associated with the WHIM at $T > 10^5$ K, it may trace cooler shock-heated gas, the metal-enriched LAF or photoionized regions in the extended haloes of galaxies.
There are two principal mechanisms for the ionization of the gas being considered here: photoionization by the UV background and collisional ionization. The characteristics of photoionized gas depend on the shape and strength of the ionizing spectrum and on the density of the gas, while the properties of collisionally ionized gas depend principally on the temperature of the gas. Gas that is predominantly photoionized will have characteristic temperatures of the order of a few times $10^4$ K. Collisional ionization models of IGM absorbers are usually constructed to explain highly ionized gas and adopt temperatures $\sim 10^5$ K and above (e.g. Cen & Fang 2006; Gnat & Sternberg 2007), although lower temperatures are affected by collisions as well.

The presence of strong O $\text{VI}$ in the absorber being studied here may arise due to the photoionization of a low-density absorber, the presence of hot gas or gas that has cooled from high temperatures in an NEQ manner, or from a mixture of these. In this section, we consider pure photoionization and pure collisional ionization models for the gas making up this absorber. We also investigate an admixture of photoionized and collisionally ionized material, a scenario with some support from the comparison of the O $\text{VI}$ and C $\text{III}$ or O $\text{IV}$ velocity structure. Though there are likely regimes in which either photoionization or collisional dominates, IGM gas will have contributions from both of these mechanisms: photons will be present in intergalactic space and collisional ionization is important for at least hydrogen above $\sim 10^3$ K. Sophisticated models that account for the impact of both are beyond the scope of this paper (see Cen & Fang 2006; Wiersma, Schaye & Smith 2008 for recent attempts at such models within large-scale simulations). We consider a small number of models in which high-temperature gas is exposed to ionizing photons, though ours is not an extensive exploration of that approach.

We assume that the observed H I and metal ions in this absorber are nearly co-spatial and that the absorber has uniform abundances. We use solar relative abundances as a starting point for comparing ions of C, N, O, Ne and Mg to models. Unfortunately, there is some controversy about the relative abundances of these elements in the Solar system. Meteoritic abundances of Mg are well-determined and give a good abundance measure for the Solar system (with the Mg to Si abundance in meteorites being referenced to the photospheric Si abundance to provide an absolute Mg abundance); we adopt the Si abundance to provide an absolute Mg abundance); we adopt the Si abundance in meteorites being referenced to the photospheric Mg abundance to provide an absolute Mg abundance). We assume that the observed H I abundance is that in the corona, and we assume Ne/O = 0.15 or log Ne/O = $-0.82$ (e.g. Asplund, Grevesse & Sauval 2005a; Basu & Antia 2008).

Solar system abundance estimates for C, N and O depend on photospheric abundances (see recent overviews by Lodders 2003; Asplund et al. 2005a; Lodders et al. 2009). Recent adoption of 3D hydrodynamic models in analyzing the photospheric data has led to significantly lower abundances (see Asplund 2005) than earlier results (e.g. Anders & Grevesse 1989). This is particularly true for O, for which Asplund et al. (2004) derive log O/H = $-3.34$ ± 0.05 compared with the earlier standard of log O/H = $-3.17$ ± 0.06 (e.g. Grevesse & Sauval 1998). Such a low abundance causes significant difficulties with helioseismology models (e.g. Bahcall et al. 2005; Basu & Antia 2008), and there are arguments in favour of the higher abundances (e.g. Delahaye & Pinsonneault 2006; Ayres 2008, and others).

We will proceed by following the recent critical summary of abundances by Lodders et al. (2009) and assume log O/H = $-3.27$ ± 0.07 (an average of values from Caffau et al. 2008; Ludwig & Steffen 2008; Melendez & Asplund 2008). With our adopted Solar system Ne/O ratio, this implies log Ne/H = $-4.09$.

The abundance of C advocated by Lodders et al., log C/H = $-3.61$ ± 0.04 (an average of results from Allende-Prieto et al. 2002, Asplund et al. 2005b and Scott et al. 2006), is less controversial. Lodders et al. recommend log N/H = $-4.14$ ± 0.12 from Caffau et al. (2009); though this result has not yet appeared in press we adopt this value for consistency. For comparison, Asplund et al. (2005a) advocate log N/H = $-4.22$ ± 0.06.

### 4.1 Collisional ionization models

Ionization of metals by collisions (primarily with electrons) can lead to high-stage metal ions if the gas temperature is sufficiently high. This is what drives the WHIM models, in which the high temperatures are a result of high-velocity shocks as gas accretes on to filaments, groups and clusters of galaxies (e.g. Furlanetto et al. 2005; Kang et al. 2005; Bertone et al. 2008; Cen & Ostriker 1999; Davé et al. 1999). These works emphasize the potential importance of O $\text{VI}$ for tracing this material, though several cosmological simulations also predict that some of the O $\text{VI}$ likely traces cool, photoionized gas (e.g. Cen et al. 2001; Fang & Bryan 2001, Chen et al. 2003; Kang et al. 2005; Oppenheimer & Davé 2009).

Given the strong O $\text{VI}$ in the absorber studied here, it is worth considering if the ionization of the absorber can be explained primarily through collisional ionization. We use the recent models of Gnat & Sternberg (2007) to test whether collisional ionization can explain the relative distribution of ionization states in the $z = 0.495$ absorber towards PKS 0405$-$123. These authors have calculated new collisional ionization calculations with up-to-date atomic physics. They discuss models under the assumption of CIE as well as NEQ cooling models in which gas initially at $T = 5 \times 10^5$ K cools isochorically or isobarically.

One may argue against single-temperature CIE models for this absorber without detailed calculations, as the profile fits to the C $\text{III}$ profiles suggest temperatures well below the $T \gtrsim 10^5$ K needed to produce significant O $\text{VI}$ absorption in CIE. A comparison of the ionic ratios for the species in Table 1 shows no single temperature for which all of the data can be matched by the CIE models. This is demonstrated in Fig. 7, which shows the column density ratios predicted by the Gnat & Sternberg CIE models for a number of species, identifying temperatures over which the models are consistent with the data for each of the ratios. The difficulties are principally in simultaneously matching the ratios of C $\text{III}$ to O $\text{VI}$ and limits on O $\text{III}$ to C $\text{III}$. Prochaska et al. (2004) and others have emphasized that C $\text{III}$ and O $\text{VI}$ cannot coexist in significant amounts in single-temperature CIE models. The temperature limits derived for the C $\text{III}$ in this absorber provide support for this conclusion.

The column densities may be better matched if one assumes a two-temperature structure for the absorber, with both phases in CIE. In this ad hoc model, one assumes that the O $\text{VI}$ traces a warm-hot phase and that the C $\text{III}$ traces a separate warm phase, perhaps a low-temperature WHIM like that discussed by Kang et al. (2005). The upper and lower panels of Fig. 7 show the constraints for each of the independent temperature regimes. The temperature of the O $\text{VI}$-bearing medium is constrained to be in the range $2.3 \times 10^4 \leq T \leq 4.7 \times 10^5$ K by the upper limits for O $\text{III}$ and Ne $\text{VII}$ at the low and high end of the range, respectively. In this case, the C $\text{III}$-bearing gas, if in CIE, would itself require $T \lesssim 10^5$ K based on the O $\text{III}$ to C $\text{III}$ ratio, consistent with the C $\text{III}$ $T$-values. In this scenario, O $\text{VI}$ and O $\text{V}$ are present in both temperature regimes, though most of
Figure 7. Column density ratios of several ions relative to C\textsc{iii} (top) and O\textsc{vi} (bottom) as a function of temperature for the CIE models of Gnat & Sternberg (2007). The solid lines represent regions for which each of the ratios is consistent with the observations of the $z \approx 0.495$ absorber towards PKS 0405−123. Note that the O\textsc{iii}/C\textsc{iii} and O\textsc{iii}/O\textsc{vi} ratios cannot be simultaneously matched for any temperatures. Furthermore, the C\textsc{iii}/O\textsc{vi} ratio is not matched for temperatures consistent with the linewidth of the C\textsc{iii}. (The narrow range of temperatures for which C\textsc{iii}/O\textsc{vi} is matched is denoted by the diamond in the bottom panel.) The full range of temperatures is not shown in each panel because of the limited range of temperatures over which Gnat & Sternberg find significant amounts of C\textsc{iii} and O\textsc{vi}. The NEQ ratios have similar distributions at $[M/H] = −1$. Those at solar abundance have significantly more O\textsc{vi} at lower temperatures and similar difficulties matching all of the available ionization states.

these ions must reside in the O\textsc{vi}-bearing phase for the C\textsc{iii}-bearing phase to be at $T \lesssim 10^6$ K. This is very difficult to reconcile with the breadth of the O\textsc{iv} profile, and the limit derived in Section 3.1.4 for the fraction of that profile that can be associated with hot gas. Of course, one may posit a distribution of temperatures, but the models will become increasingly complex and difficult to justify in the face of the relatively simple assumptions that one makes when adopting CIE models. In view of these arguments, pure CIE models are not a good representation of the ionization of this absorber.

Shock-heated WHIM gas may not, however, be in equilibrium. If hot gas cools faster than it can effectively recombine, the gas may be overionized for its temperature (e.g. Shapiro & Moore 1976; Edgar & Chevalier 1986; Sutherland & Dopita 1993; Heckman et al. 2002); in addition, if the ion and electron temperatures of shock-heated gas are significantly different, NEQ conditions also hold (see Cen & Fang 2006; Yoshikawa & Sasaki 2006; Bertrone, Schaye & Dolag 2008). The comparison of the relative time-scales for cooling, ionization and recombination is a measure of whether such NEQ ionization is important. Tripp et al. (2008) discuss these time-scales for the IGM; unfortunately, they could not conclusively argue for or against NEQ effects being important for the WHIM. Recently, Wiersma et al. (2008) have argued that photoionization of metal coolants can suppress cooling in the IGM, increasing the cooling time significantly. If so, this argues NEQ cooling effects are likely not important.

Gnat & Sternberg (2007) have produced NEQ models that follow the ionization fractions of metal ions as gas cools from an initial temperature of $T = 5 \times 10^6$ K. The resulting ionization fractions are metallicity dependent. We have considered models with solar and 10 per cent solar metallicity (see Sections 4.2 and 4.3). For many species, the NEQ models approach the CIE models at low metallicity (Gnat & Sternberg 2007; Tripp et al. 2008), O\textsc{vi} being one of those for which NEQ models at $[M/H] = −1$ are quite similar to CIE models. Given this similarity, it is not surprising that the NEQ models have nearly the same difficulties as the CIE models. The C\textsc{ii}/O\textsc{vi} ratio is only matched at $T \approx 1.9 \times 10^5$ K for the Gnat & Sternberg isobaric\textsuperscript{6} models at both metallicities, inconsistent with the $b$-values for C\textsc{ii} and with the O\textsc{iii} upper limits. Two-temperature NEQ models can be constructed as discussed above for the CIE models, but all require most of the O\textsc{iv} to be associated with gas at temperatures $\sim 2 \times 10^5$ K, which is inconsistent with our component-fitting analysis. For solar abundance models, the limit to the O\textsc{iii}/C\textsc{iii} ratio requires $T < 2 \times 10^4$ K in the NEQ models, inconsistent with other constraints in this case (e.g. from O\textsc{ii}).

Thus, it is unlikely that the gas making up the $z = 0.495$ absorber towards PKS 0405−123 is dominated by collisional ionization. This holds when considering either CIE or NEQ models. If our observations had only measured H\textsc{i}, C\textsc{iii} and O\textsc{vi}, a common situation in IGM observations, these models could possibly be questioned by considering the component structure for this absorber. However, given the low S/N ratio of these and other STIS observations of the low-$z$ IGM, it would be difficult to strongly rule them out.

4.2 Photoionization models

The $z = 0.495$ absorber is exposed to the ultraviolet background (UVB) from the integrated light of QSOs and galaxies in the universe. As such, photoionization will play a role in determining the ionization of the gas, which is optically thin to ionizing radiation, even if collisions are the dominant ionization mechanism (Wiersma et al. 2008). Here, we consider models in which collisional ionization is unimportant, and the ionization state of the absorber is determined by photoionization alone. In this scenario, the absorber amounts to a metal-enriched LAF cloud.

For optically thin systems, the ionization state of photoionized gas is primarily determined by the ratio of the ionizing photon to hydrogen volume densities, i.e. the ionization parameter $U \equiv n_\nu / n_H$, and the spectral shape of the ionizing background. The metallicity can have a minor effect on the ionization through its importance for the thermal balance. We use the CLOUDY ionization code (version 07.02; last described by Ferland et al. 1998) to model the photoionization of a plane-parallel slab of gas illuminated by a diffuse UVB. Because this is intrinsically a one-dimensional model, it is effectively an infinite thin sheet diffusely illuminated on both sides by the UVB. We stop the calculations when the integrated H\textsc{i} column matches that observed. Our models vary the density for the assumed ionizing spectra (see below), which is akin to varying the ionization parameter. We assume solar relative abundances for the initial models with a base metallicity of $[O/H] = −0.5$ and adjust the metallicity at a later point to best match the total column densities of the ions. The metallicity plays only a small role in the relative ratios of the metal ions, although it fixes the ratio of metal ions to H\textsc{i}.

We investigate two possible models for the ionizing background at $z \approx 0.5$ from the Haardt & Madau (in preparation; details given in Haardt & Madau 2001) update to the work by Haardt & Madau (1996). These background spectra, calculated with the CUBA software (Haardt & Madau 2001), assume that (1) the UVB is dominated

\textsuperscript{6}Gnat & Sternberg (2007) discuss the conditions over which isobaric or isochoric models are likely to be appropriate. This absorber is near the cross-over point, though more likely to be in the isobaric regime. Isochoric models give very similar results.
by quasars and active galactic nuclei (the QSOs-only spectrum) or (2) the UVB is a combination of light from quasars and integrated light escaping from galaxies (the QSOs+galaxies spectrum). The input QSO spectrum in these models uses a power-law index of $\alpha = 1.8$ for wavelengths below 1050 Å (e.g. Zheng et al. 1998; Telfer et al. 2002), while the basic spectral shape for the light leaking from galaxies is based on a spectrum from Bruzual & Charlot (1993, 2003) libraries for a population of stars with 0.2 solar metallicity and 0.5 Gyr age. The ionizing ($h\nu > 1$ Ryd) radiation coming from the galaxies is attenuated by the gas and dust within the galaxies. The escape fraction of ionizing gas from the galaxies is an important quantity for calculating the background, and Haardt & Madau adopt $f_{esc} = 0.1$ in their base model (F. Haardt, private communication). As noted by Haardt & Madau (2001), the definition of the escape fraction in this model is not the ratio of escaping Lyman continuum photons to those produced by the underlying stellar population. Rather, this value is normalized to the observed (i.e. dust attenuated) 1500 Å flux of galaxies (see equation 1 in Haardt & Madau 2001). In the QSOs+galaxies spectrum, the majority of the hydrogen ionizations are caused by photons that have escaped from galaxies.

Fig. 8 shows the results of our photoionization models for the QSOs-only (left-hand panel) and QSOs+galaxies (right-hand panel) spectra. We plot the ratio of column densities of $\text{O\ III}$, $\text{O\ IV}$, $\text{O\ V}$ and $\text{O\ VI}$ to $\text{C\ III}$ from the CLOUDY models as a function of the ionization parameter assuming solar relative abundances. The thick solid lines denote regions of the models for which the calculated ratios are consistent with observed column densities. While we have plotted the $N(\text{X})/N(\text{C\ III})$ ratios, the thick lines are based on all of the available constraints. These plots do not include all of the ions for which we have limits, as many of the model values are well below the upper limits for this absorber. Also, the ions of nitrogen are not used to constrain the ionization. Non-solar N/C or N/O ratios are common at moderately low metallicities, and we use the $\text{N\ IV}$ column to estimate the N/O ratio in the absorber. When using $\text{O\ IV}$ we have been conservative, since we are concerned that the component fitting results may not fully account for the saturation in the profile; we adopt the lower limit derived from integrating the $N_e(\nu)$ profile of $\text{O\ IV}$. The models that fall within 1σ of the component fitting column are also shown with a black line in Fig. 8.

The best-fitting models for the QSOs-only spectrum have log $U \approx -1.28 \pm 0.03$, which matches all of the column density constraints from Table 1. The quoted uncertainties in the ionization parameter represent the range over which the models are within 1σ of the observed ratio. The constraints on the models rely on most of the available ions, but the most important are the $\text{O\ VI/C\ III}$, $\text{O\ III/O\ IV}$ and $\text{O\ IV/O\ VI}$ ratios. The constraints are significantly less stringent without the inclusion of the $\text{O\ III}$ limits.

The metallicity implied by these models is $[\text{O/H}] = [\text{C/H}] = -0.15 \pm 0.07$, where the uncertainty accounts for the range of ionization parameters and observational uncertainties, but does not attempt to account for any systematic uncertainties associated with the choice of UVB, adopted Solar system abundances, missing atomic data or model assumptions. For our adopted UVB, these models have $n_{\text{H}} \approx 5.0 \times 10^{-6}$ cm$^{-3}$ and log $N(\text{H}) \approx 18.5$, giving a pathlength for the model cloud of $\sim 20$ kpc. The derived density is similar to the predictions for average LAF cloud of this column density from the models of Schaye (2001) and Davé et al. (1999), both of which predict $n_{\text{H}} \approx 10^{-5}$ cm$^{-3}$. The simulations show a large scatter in the $\rho/N(\text{H})$ relation and have factor of a few type.

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Footnote 7: One could imagine that the absorber were near to an individual galaxy and estimate the ionizing spectrum seen from that galaxy as a function of distance, as, for example, Fox et al. (2005) have done for studying high-velocity clouds about the Milky Way. The present models attempt to study the effects of the integrated light escaping from the overall population of galaxies.
uncertainties. The neutral fraction of hydrogen for this model is $x(H) \equiv N(H)/N(H) \approx 6 \times 10^{-5}$. CLOUDY predicts equilibrium temperatures $T \approx 28,000$ K for both assumed UVB models.

The best-fitting models based on the QSOs+galaxies spectrum match the available constraints for $\log U \approx -0.87 \pm 0.03$, corresponding to $n_H \approx 3.5 \times 10^{-5}$ cm$^{-3}$ for this spectrum. The metallicity implied by this model is $[O/H] = [C/H] \approx -0.62 \pm 0.07$, nearly 0.5 dex lower than that derived using the QSOs-only UVB. This model has $\log N(H) \approx 19.0$, giving a pathlength for the model cloud of $\sim 90$ kpc. Thus, the fraction of neutral hydrogen is $x(H) \approx 2 \times 10^{-5}$.

The larger ionization fraction of H and ionization parameter in the QSOs+galaxies models comes about because the radiation leaked from galaxies contributes significantly more photons between 1 and 4 Rydbergs. Thus, to produce O\textsc{iv} and O\textsc{vi} columns comparable to those in the QSOs-only models requires more H-ionizing photons (and C\textsc{iii}-ionizing photons).

For both choices of UVB, comparing the measured O\textsc{iv} column density with those predicted by the models gives $[N/O] \approx -0.60^{+0.10}_{-0.16}$. This value of [N/O] is consistent with [N/O] seen in metal-poor galaxies and damped Ly\alpha systems at similar metallicities (see Henry & Prochaska 2007; Pettini et al. 2008). It is difficult to assess the significance of this result given the uncertainties in both the models and the data. Though, given the significant differences in total metallicity between the two UVB models, it is encouraging that both give the same [N/O] results.

We have assumed a solar C/O ratio in the above analysis. Danforth et al. (2006) have made some arguments for [C/O] $\approx -1$ in low-$z$ O\textsc{vi} + C\textsc{iii} systems (their equation 15; see also Danforth & Shull 2008), although they view this result with a great deal of scepticism. We have enough information from the oxygen ions alone to test whether the present absorber has such a low value. Using only the oxygen ions to constrain models using the QSOs-only UVB, the ionization parameter is constrained to be $\log U = -1.36 \pm 0.10$. This model gives $[O/H] = 0.0 \pm 0.2$, i.e. solar abundance, with $[C/O] = -0.2 \pm 0.1$ and $[N/O] = -0.7 \pm 0.2$. Adopting the QSOs+galaxies models leads to $\log U = -0.92 \pm 0.10$. This model gives $[O/H] = -0.5 \pm 0.2$, $[C/O] = -0.1 \pm 0.1$ and $[N/O] = -0.7 \pm 0.2$. Thus, for these assumed UVB, the data do not support a C/O ratio as low as 0.1 times solar.

A slightly sub-solar C/O abundance is consistent with our models, although solar C/O is not ruled out. Allowing the C/O to be sub-solar affects the derived [O/H] abundances moderately. Notably, the QSOs-only model produces a solar oxygen abundance, which seems unlikely for an absorber arising in the diffuse IGM; however this absorber, given its large O\textsc{iii} column, may arise near to a galaxy. We will discuss the implied abundances further in Section 5.

### 4.3 Multiphase models

We have shown above that a pure photoionization model can match the constraints provided by the ion column densities in this absorber. Even the O\textsc{vi} can be adequately explained by photoionization by the diffuse UVB. The C\textsc{iii} and O\textsc{iv} profiles are well fit with relatively narrow components (see Table 2) implying low-temperature gas consistent with photoionization, although we have some concern about the limits from the O\textsc{iv} fits as discussed above. The component structure of O\textsc{vi} is not as clearly delineated. This may simply be due to the low S/N of the observations, but could also imply broader components in O\textsc{vi} than the lower ions. The O\textsc{vi}/C\textsc{iii} ratio varies somewhat with velocity in the profile, albeit at moderate significance. Furthermore, there is room within the O\textsc{iv} profile for a broad component tracing warm-hot gas ($T \gtrsim 10^5$ K) that contributes as much as $\sim 30$ per cent of the O\textsc{iv} column. The breadth of the C\textsc{iii} profile suggests high-temperature collisionally ionized gas cannot be important for that ion (and, indeed, this is not expected; see Prochaska et al. 2004). While the evidence is not firm, this absorber could plausibly contain regions of differing metal ion ratios and perhaps different ionization mechanisms and temperatures (Section 3.1.4). The evidence for multiphase absorption is certainly not as clear-cut as some cases, for example, emphasized in the Tripp et al. (2008) survey of low-$z$ systems.

Here, we consider a multiphase model for the ionization of the $z \approx 0.495$ absorber. In our model, the column densities are predicted using a linear combination of the pure collisional ionization and photoionization models considered above (see e.g. Prochaska et al. 2004). The free parameters are the ionization parameter of the photoionized component, the temperature of the collisionally ionized component, the fraction of the total hydrogen column associated with the collisionally ionized medium, $\phi_{\text{coll}}(H)$, and the metallicity of the gas, assumed to be the same between phases. This is meant as a crude model of a cool, photoionized cloud surrounded by shock-heated hot gas. We note that this model is not self-consistent in that neither is the collisionally ionized phase subjected to an ionizing radiation field nor is the photoionized phase subject to radiation from the hot, collisionally ionized phase. We are thus assuming that collisional processes do dominate the ionization of the hot phase that the UVB does not have a significant impact on this phase while the radiation from that hot phase is not intense enough to rival the UVB in importance for the photoionized phase.

The results of these models are shown in Fig. 9, which shows the range of allowed values for $\phi_{\text{coll}}(H)$, $\phi_{\text{coll}}(\text{O}\text{iv})$ and $\log N(H)$ as a function of temperature for models adopting the QSOs-only or QSOs+galaxies spectra of Haardt & Madau (in preparation) and Gnat & Sterberg (2007) CIE models. Here, $\phi_{\text{coll}}(H)$ and $\phi_{\text{coll}}(\text{O}\text{iv})$ are the fractions of the total H and O\textsc{vi} columns that arise in the hot, collisionally ionized gas. These models assume that $\lesssim 30$ per cent of the O\textsc{iv} arises in the collisionally ionized phase [i.e. $\phi_{\text{coll}}(\text{O}\text{iv}) \lesssim 0.3$]. If this limit is relaxed, a broader range of contributions from the hot, collisionally ionized phase is allowed for temperatures $\log T \lesssim 5.6$, although the higher temperature results are not much affected. These models assume CIE, but the NEQ models give results that are not significantly different. Our calculations extend over the temperature range $4.5 \leq \log T \leq 6.5$, although models for $\log T \lesssim 5.30$ ($T \lesssim 2 \times 10^5$ K) did not produce models in agreement with the observations. The ionization parameters are not shown because they differ little from the values derived in the pure photoionization models discussed above (Section 4.2). Because we are interested in the origins of the O\textsc{vi}, these plots only show models for which $\phi_{\text{coll}}(\text{O}\text{vi}) \geq 0.05$. This is the cause of the apparent lower limit to the total H column densities. If we do not require that the collisionally ionized phase contribute to the O\textsc{vi} column densities, the lower right of the top and bottom panels in these figures would both be allowed (see Section 5).

We find multiphase models that are consistent with our observational constraints for $T \gtrsim 2.2 \times 10^5$ K ($\log T \gtrsim 5.35$) for both adopted UVB spectra. The ionization parameters appropriate for the photoionized phase are similar to those reported in Section 4.2. They differ from the pure photoionized models by up to $-0.2$ and $+0.05$ dex, i.e. the maximum excursions are to lower ionization parameter. For temperatures $T \sim 2.8 \times 10^5$ to $5 \times 10^5$ K ($\log T \approx 5.45$ to 5.70), we have very little constraint on the fractions of H or O\textsc{vi} arising in the collisionally ionized gas, largely because we only have limits to the O\textsc{iv}/O\textsc{vi} ratio. Thus, there is a degeneracy between the collisionally ionized phase and the photoionized phase.
for the oxygen ions where one phase may compensate for the other. The C\textsc{iii} still arises almost exclusively in the photoionized phase.

The metallicities in these mixed-phase models are very similar to those derived from pure photoionization models. The range of allowed metallicities for the QSOs-only UVB models is \([\text{O}/\text{H}] \sim -0.33\) to \(-0.05\); for the QSOs+galaxies UVB we find \([\text{O}/\text{H}] \sim -0.76\) to \(-0.52\). This is quite insensitive to the assumptions for \(T \gtrsim 5 \times 10^5 \text{ K} \) since the collisionally ionized phase contributes little to the detected ions, which are all associated with the photoionized phase save for a small fraction of O\textsc{vi}.

Thus, a simple multiphase model with distinct collisionally ionized and photoionized regions allows for significant amounts of hot gas. For temperatures \(T \gtrsim 5 \times 10^5 \text{ K}\), this is due to the nature of the observational constraints. We do not detect Ne\textsc{viii} or Mg\textsc{x}, and these are the only ions covered by our observations with significant ionization fractions at these temperatures. At temperatures \(T \sim 2.8 \times 10^5\) to \(5 \times 10^5 \text{ K}\) (\(5.45 \lesssim \log T \lesssim 5.70\)), the fraction of the total column of hydrogen allowed to be associated with the collisionally ionized phase may be significant and is poorly constrained.

We find none of these models matches all of the available constraints for a collisionally ionized phase at temperatures \(T \lesssim 2 \times 10^6 \text{ K}\).

Another type of multi-process model is one in which gas at a fixed temperature is irradiated by the UVB (e.g. Danforth et al. 2006; Tripp et al. 2008). In this approach, we fix the gas temperature within our \textsc{Cloudy} models, which provides for collisional ionization, and calculate the ionization balance for a range of ionization parameters at each temperature. This is effectively a collisionally ionized gas that is modified by the UVB ionization. For both UVB models investigated here, the models are only able to match the available constraints for \(T \lesssim 40000 \text{ K}\), consistent with the \(b\)-values of components seen in C\textsc{iii}. The main difficulty is in avoiding overproduction of O\textsc{iii} at high temperatures. The allowable ionization parameters, set by the O\textsc{vi}\textsc{c}/C\textsc{iii} ratio, are similar to those discussed above, with \(\log U \approx -0.85 \pm 0.05\). This model also gives a similar abundance with \([\text{O}/\text{H}] \approx -0.70 \pm 0.05\). Similarly, the models assuming a QSOs-only UVB spectrum give \([\text{O}/\text{H}] \approx -0.27 \pm 0.05\) at \(\log U \approx -1.23 \pm 0.05\). A single-temperature, collisionally ionized gas exposed to the UVB, then, is inconsistent with our...
observations for the large temperatures consistent with the WHIM, \( T \sim 10^3 \) to \( 10^5 \) K. Indeed, the temperatures allowed by this approach are generally so low that they approach those produced by a pure photoionization model (which gives \( T \sim 28000 \) K).

5 DISCUSSION

We have presented measurements of five metal ions and limits on another eight in the \( z \approx 0.495 \) absorber towards PKS 0405–123. We have discussed a range of possible ionization mechanisms, determining that this absorber may be described by a pure photoionization model, but may also harbour some collisionally ionized material at \( T \gtrsim 10^5 \) K if it is mixed with a cool photoionized component.

5.1 The WHIM and low-\( z \) O\( \text{VI} \) systems

Intervening O\( \text{VI} \) absorption-line systems are quite common at low redshifts, with \( \Delta N/\Delta z \approx 10–20 \) for \( W_c \gtrsim 30 \) m\( \text{Å} \) (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008a) depending on the criteria used to select the O\( \text{VI} \) systems. Thus, they probe a significant baryon reservoir no matter their origin. However, they have elicited the most interest because they may trace the ‘missing baryons’ associated with a WHIM. For systems with \( W_c \gtrsim 200 \) m\( \text{Å} \) like the one studied here, the absorber density is significantly lower, of course, with \( \Delta N/\Delta z \approx 2 \) (Tripp et al. 2008).

Some intervening absorbers with significant O\( \text{VI} \) absorption likely do trace the WHIM. These may be absorbers with signatures of pure collisionally ionized gas at high temperatures, such as the systems at \( z \approx 0.31978 \) towards PG 1259+593 from Richter et al. (2004) or at \( z \approx 0.1212 \) towards H1821+643 discussed by Tripp et al. (2001), in which O\( \text{VI} \) and H\( \text{I} \) have breadths consistent with \( T \approx (2–3) \times 10^5 \) K. These may also be found in absorbers that are part of a multiphase structure including a very hot component \( (T \gtrsim 5 \times 10^5 \) K) such as the Ne\( \text{VIII} \)-bearing system at \( z \approx 0.207 \) towards HE 0226–4110 (Savage et al. 2005). There are reasonable arguments for the origins of other absorbers in hot shock-heated gas, such as the \( z \approx 0.056 \) systems towards PKS 2155–304 that Shull, Tumlinson & Giroux (2003) have argued trace material infalling on to a group of galaxies (which may exhibit X-ray absorption; Fang et al. 2002). However, for most O\( \text{VI} \) absorbers, the connection to the WHIM is less evident or non-existent (Prochaska et al. 2004; Lehner et al. 2006). In their survey of \( z \lesssim 0.4 \) O\( \text{VI} \) systems, Tripp et al. (2008) find \( \gtrsim 34 \) per cent of their intervening absorbing components are associated with cool gas at \( T < 10^5 \) K based on an analysis of \( b \)-values. Thus, a significant fraction is obviously too cool to be associated with the \( T > 10^5 \) K WHIM, although they may represent cooled WHIM material (e.g. Kang et al. 2005). However, \( \sim 50 \) per cent of that sample shows significant differences between the H\( \text{I} \) and O\( \text{VI} \) profiles, suggesting a multiphase structure. Such absorbers could include gas at \( T \gtrsim 10^5 \) K.

While the origins of O\( \text{VI} \) in the IGM may be ambiguous, with photoionization being a significant contributor to the O\( \text{VI} \) in a significant number of absorbers (e.g. Kang et al. 2005; Tripp et al. 2008; Thom & Chen 2008b; Oppenheimer & Davé 2009), the Li-like ions Ne\( \text{VIII} \) and Mg\( \text{X} \), which peak in abundance in CIE models at \( T \approx 6.4 \times 10^5 \) K and \( 1.1 \times 10^6 \) K, respectively (Gnat & Sternberg 2007), are much more secure probes of shock-heated hot gas. These ions are probes of WHIM material at temperatures where a significant fraction of the low-\( z \) baryons are expected to reside (Davé et al. 2001) and probe gas in the temperature regime accessible via X-ray absorption studies \( (5 \times 10^5 < T < 3 \times 10^6 \) K). The absorber considered here is one of the few O\( \text{VI} \) absorbers for which Ne\( \text{VIII} \) could be searched (Prochaska et al. 2004; Richter et al. 2004; Savage et al. 2005; Lehner et al. 2006), and the only one for which a limit on Mg\( \text{X} \) is currently available. A summary of previous observations of Ne\( \text{VIII} \) in the low-\( z \) IGM is given in table 7 of Lehner et al. (2006). Ne\( \text{VIII} \) has only been detected in the multiphase absorber at \( z \approx 0.207 \) towards HE 0226–4110 (Savage et al. 2005), the system with the second highest \( W_c (\text{O}\text{VIII} 1031) = 169 \pm 15 \) m\( \text{Å} \) among those yet searched for Ne\( \text{VIII} \) (the highest being the current absorber). Savage et al. derive \( N(\text{Ne}\text{VIII})/N(\text{O}\text{VIII}) = 0.33 \pm 0.10 \) for this absorber with \( \log N(\text{O}\text{VIII}) = 14.37 \pm 0.03 \).

Our 3\( \sigma \) limit to the Ne\( \text{VIII} \) column density gives the lowest limit on this ratio yet observed, \( N(\text{Ne}\text{VIII})/N(\text{O}\text{VIII}) < 0.18 \) (3\( \sigma \)) assuming the O\( \text{VIII} \) derived from integrating the full profiles (see Section 3.1.3); a slightly higher value of \( \lesssim 0.21 \) is derived if one includes the O\( \text{VIII} \) in the velocity ranges of components 1, 2 and 3. The O\( \text{VIII} \) equivalent width of this system is 25 per cent larger than that for the \( z \approx 0.207 \) absorber towards HE 0226–4101.

The lack of Ne\( \text{VIII} \) and Mg\( \text{X} \) absorption in the \( z \approx 0.495 \) absorber towards PKS 0405–123 implies that there is not a very large reservoir of hot \((\sim (0.5–3) \times 10^5 \) K\), collisionally ionized gas associated with this absorber, although the precise limits depend on the temperature of the gas. Such hot gas would not be detectable in the other ions probed by our observations due to its high temperature (and hence ionization state). Fig. 10 shows limits to the total H column density as a function of temperature for gas associated with the WHIM in this absorber assuming [M/H] \( \approx -0.62 \) (from the models adopting a QSOs+galaxies UVB). The distribution of these limits with temperature arises from jointly considering the O\( \text{VIII} \), Ne\( \text{VIII} \) and Mg\( \text{X} \) ionization fractions and observational limits on their columns. The limits from the individual ions assuming CIE are shown by the grey lines. At \( T < 5.7 \), we assume the results from Fig. 9 for a multiphase absorber. The H column density limits displayed in Fig. 10 are lower if one assumes a higher metallicity (e.g. from models with the QSOs-only UVB).

![Figure 10](image-url)
Two things are important from this figure. First, if additional hot gas is present with temperatures \( \log T \lesssim 6.5 \), it would not provide sufficient column to lead to detectable X-ray absorption except perhaps along the sight lines to the very brightest sources. Over the range \( 6.0 \leq \log T \lesssim 6.5 \), we infer the O\textsc{vi} K\alpha line should have an equivalent width \( W_\lambda < 6 \, \text{mA} \) to \( W_\lambda < 15 \, \text{mA} \) with a column \( \log N(\text{O}\textsc{vi}) \lesssim 16.7 \) (all 3\sigma limits). These are derived from the limits on Ne\textsc{viii} and Mg\textsc{x}, assuming CIE ionization fractions and solar relative abundances (the absolute abundance is not important since the O\textsc{vii} column is predicted from other metal species). We also assume pure thermal broadening of the lines. O\textsc{vii} K\alpha would be even weaker, with a maximum of \( W_\lambda < 5 \, \text{mA} \) and \( \log N(\text{O}\textsc{vii}) \lesssim 15.75 \) for \( \log T \sim 6.5 \). The presence of O\textsc{vii} at the equivalent width limit for the highest temperatures might be marginally detectable towards bright objects (e.g. Williams, Mathur & Nicastro 2006; Fang, Canizares & Yao 2007), although this is a 3\sigma limit and absorption is very unlikely to be present at that level. Furthermore, the discrepancies discovered between various instruments and groups for X-ray absorption lines reported at good significance towards extremely bright objects make it difficult to imagine the current absorber could be reliably detected if at \( \log T \lesssim 6.5 \) (e.g. see discussion in Bregman 2007). Secondly, the limits for WHIM material at \( \log T \gtrsim 6.5 \) are quite limited due to low ionization fractions of even these highly ionized species at such temperatures. The majority of the metal-bearing WHIM is thought to be at temperatures below this (e.g. Davé & Oppenheimer 2007), with higher temperature IGM gas tracing large overdensities associated with clusters. At \( \log T \gtrsim 7 \), both the O\textsc{vii} and O\textsc{viii} transitions are limited to \( W_\lambda \lesssim 20 \) to 25 mA (3\sigma). We note that photoionization models for this absorber, which can match the available constraints quite well, predict \( \log N(H) \approx 18.5 \) to 19.0.

The Li-like ions limit the column of very hot gas in this absorber over a temperature range at which the majority of the WHIM baryons are expected to reside to be relatively low. While some of the gas in this absorber could be associated with a few times \( 10^5 \) K gas, a significant cool photoionized component is needed to explain the lower ionization species such as C\textsc{iii}. The O\textsc{vi} in this system may be described fully by a photoionized gas. However, even if some of the O\textsc{vi} is produced via collisional ionization, the absorber must include some photoionized material (with \( \sim 50 \) per cent or more of the O\textsc{vi} coming from a cool photoionized phase). Because of the uncertainties in its origins, O\textsc{vi} is not a robust, pure tracer of the WHIM in this absorber. There is no direct evidence for hot gas with \( T \gtrsim 10^5 \) K material in this absorber, even though it has very strong O\textsc{vi}. For temperatures \( T \gtrsim 5 \times 10^5 \) K, however, the gas would only be seen in Ne\textsc{vii} or Mg\textsc{x} absorption.

The absorber studied here may have a multiphase structure, where the high-temperature shock-heated gas contributes somewhat more than half of the total H column density (unless at \( T \gtrsim 5 \times 10^5 \) K, in which case we have few constraints on the gas). Tripp et al. (2008) note that \( \approx 50 \) per cent of their intervening absorbers show strong differences between the H\textsc{i} and O\textsc{vi} profiles, evidence for a possible multiphase structure. The evidence from the velocity profiles of the absorption for a multiphase structure to this system is slight at best. While the O\textsc{vii}/C\textsc{iii} seems to vary somewhat between components 1 and 2, this does not necessarily imply these components have significantly different ionization mechanisms and temperatures.

The multiphase absorbers noted by Tripp et al. typically show large discrepancies in the velocity distribution of H\textsc{i} and O\textsc{vi} absorption and/or differences in the characteristics of the detected low-ionization metals compared with O\textsc{vi}. If the present absorber does have a mixture of phases, it may indicate that the fraction of the low-\( z \) O\textsc{vi} systems with multiphase structure is larger than Tripp et al. estimate. The presently available observations from STIS and \textit{FUSE} do not probe a broad enough range of ions or measure the velocity-resolved profiles with enough S/N to constrain the structure of many systems. Future observations with the Cosmic Origins Spectrograph (COS) will provide much higher quality spectra, allowing us to detect weaker lines and study the velocity profiles at higher S/N (albeit at lower resolution than STIS). In particular, observations of C\textsc{iv} would provide significant diagnostic power (see below); better quality observations of the \( \text{H}^\circ \) transitions could allow a search for broad components therein.

Simulations predict that the highest O\textsc{vi} equivalent width systems, like that studied here, are generally the most likely to be associated with hot gas, either hot gas in the diffuse WHIM or hot gas in the halos of galaxies (Davé et al. 2001; Kang et al. 2005; Ganguly et al. 2008; Oppenheimer & Davé 2009). The environment of the absorber is pertinent to its origins, and a number of works have explored the connection between O\textsc{vi} absorbers and galaxies (e.g. Sembach et al. 2004; Tumlinson et al. 2005; Stocke et al. 2006; Tripp et al. 2006; Cooksey et al. 2008; Lehner et al. 2009; Walker & Savage 2009). Prochaska et al. (2006) have presented a galaxy redshift survey for the sight line to PKS 0405–123 (see also Williger et al. 2006). The surveys of this sight line do not provide much insight into the relationship of this absorber to galaxies. Prochaska et al. find only three \( L \sim 6L_\odot \) galaxies within 1000 km s\(^{-1}\) of the absorbers. Two of these galaxies are found within \( \sim 200 \) km s\(^{-1}\) of the absorber, but at impact parameters \( \rho \lesssim 10 \) Mpc. This survey is >80 per cent complete to \( R = 21 \) (or roughly \( L \sim 0.8L_\odot \)) and 70 per cent complete to \( R = 22 \) (\( \sim 0.3L_\odot \)). No galaxies aside from the three high-luminosity systems are found at this redshift. So, if this system is associated directly with a galaxy, the galaxy is likely to be of the order of \( L \sim 0.1L_\odot \), or less. This absorber is not at so high a redshift that it is impractical to eventually study the fainter galaxies near this absorber with 8- to 10-m class telescopes.

### 5.2 Abundances and ionization mechanisms in the low-\( z \) IGM

The metallicity of low-\( z \) IGM absorbers has been the subject of much work over the last decade. The abundance distribution of the IGM can be used to probe the extents over which galaxies expel metals, whether the metals escape the galaxies or fall back on to them, and the impact of such metal expulsion on galaxy evolution (e.g. Tumlinson & Fang 2005; Calura & Matteucci 2006; Davé & Oppenheimer 2007). The level of metal enrichment then suggests the sphere of influence over which galaxies affect the IGM, and it is an important consideration when using metal lines to calculate the baryon density of low-\( z \) IGM absorbers since in this case \( \Omega_b \propto Z^{-1} \) (e.g. Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008a).

Many low-redshift metal-line absorbers tend to show metallicites between \([\text{M/\text{H}}] \approx -1\) and 0 (Prochaska et al. 2004; Aracil et al. 2006; Lehner et al. 2006; Cooksey et al. 2008; Tripp et al. 2006), although lower metallicities are found as well (e.g. Stocke et al. 2007 and previous references). The median metallicity in the higher redshift \( z \approx 2\)–3 LAF is \([\text{M/\text{H}}] \lesssim -2\) (e.g. Schaye et al. 2003; Simcoe, Sargent & Rauch 2004; Aguirre et al. 2008), although Simcoe et al. (2006) find that the small fraction of the IGM nearest to galaxies is at metallicities close to those found at low \( z \). Generally, it is thought that significant pollution of the average diffuse IGM has to have occurred since \( z \approx 3 \) (Tumlinson & Fang 2005; Stocke et al. 2007; Davé & Oppenheimer 2007).

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Generally speaking, there are three uncertainties associated with the ionization of the $z \approx 0.495$ system towards PKS 0405−123 (and others): (1) is the source of the ionization collisional ionization, photoionization or a mixture of both? (2) If photoionization is important, what is the nature of the ionizing UVB spectrum? (3) If collisions are important, what assumptions are appropriate (e.g. CIE versus various NEQ scenarios) and are the models sufficiently sophisticated? Of course, the latter concern of the level of sophistication in the models is appropriate for all processes. The $z \approx 0.495$ absorber towards PKS 0405−123 has characteristics consistent with pure photoionization by the UVB, perhaps including radiation that has leaked from galaxies (Haardt & Madau 2001). Models of pure collisional ionization do not reproduce the observed ionic ratios in this absorber. Multiphase models that include the effects of ionization via both photons and electron collisions are also broadly consistent with the observed ionic ratios in this absorber. Even in these models, however, the majority of the observed ions likely trace warm photoionized material.

The choice of one or the other of the ionizing backgrounds considered here is an important one, as they give significantly different metallicities for the absorber, ranging from $[O/H] \approx −0.62$ for the QSOs+galaxies UVB to $\approx −0.15$ for the QSOs only spectrum. Thus, the choice of one of two reasonable UVB spectra (and other UVB prescriptions exist) gives metallicities discrepant by ~0.5 dex, or a factor of 3. The difference comes about because the QSOs+galaxies model requires more H-ionizing photons to match the O vi column. Thus, for the same O iv/O vi or O vii/C ii ratio, the neutral fraction, $x$(H i), is lower in the QSOs+galaxies model, implying a larger total H column density for the same metal ion columns. This difference can have significant consequences for understanding the enrichment of the low-z IGM and the low-z baryon budget.

Thus, there is a large systematic uncertainty associated with the choice of ionizing background model (e.g. see discussions in Giroux & Shull 1997; Schaye et al. 2003; Tripp et al. 2008), one that is not always explicitly considered in the study of the low-z IGM. There are several plausible UVB models available, such as those dominated by AGN or QSOs with varying spectral slopes (e.g. Mathews & Ferland 1987; Telfer et al. 2002) or those containing contributions from ionizing radiation that has escaped galaxies (e.g. the Haardt & Madau spectrum adopted here).

Determining the spectral shape of the UVB is an on-going challenge. We have shown that the $z \approx 0.495$ absorber towards PKS 0405−123 can plausibly be ionized via photoionization by a UVB including a contribution from galaxies with $f_{ion} \sim 0.1$. There is some evidence for a significant contribution to the UVB from galaxies. Faucher-Giguère et al. (2008) have recently presented evidence based on the ionization rate of the $z \approx 2–4$ LAF that galaxies may dominate the ionizing UVB over much of that range, although the extent to which they contribute at low redshift is less well constrained.

The UVB may also be spatially variable, depending on the proximity of the absorber to galaxies or AGN; thus, the specific shape adopted may depend on unknown properties of the absorber. Reimers et al. (2006) have argued such variation is likely for $z \approx 2$ O vii absorbers, and there is strong evidence for a varying UVB spectral shape from the He ii forest at $z \approx 2.5$ (e.g. Kriss et al. 2001; Shull et al. 2004). Oppenheimer & Davé (2009) have also argued for a spatially variable ionizing background in order to explain the broad range of observed O vii/H i ratios (Tripp et al. 2008; Thom & Chen 2008b) compared with their simulations. If the UVB can have significant contributions from relatively local sources, leaky low-luminosity galaxies ($L \lesssim 0.1L_\odot$) are most likely to influence the ionization of the present absorber given the lack of high-luminosity galaxies with low impact parameter to the QSO sight line (Prochaska et al. 2006; see Section 5.1).

Our data do not provide sufficient diagnostics to distinguish between the two UVB models investigated here. One would ideally like to use a large number of ionic measurements to constrain the contribution of galaxies to the UVB and the spectral slope of the higher energy component dominated by AGN. A larger sample of low-z absorbers for which several ionization stages of oxygen can be measured will be collected with the upcoming COS; these may be useful in discriminating UVB spectral shapes. The transitions from O ii, O iii, O iv and O v are shifted into the COS bandpass for redshifts $z \approx 0.38, 0.38, 0.46$ and 0.83, respectively. Thus, one will have access to O ii −O iv+O vi for $z \approx 0.5$ absorbers with COS. As discussed below, the addition of C iv observations so that multiple ionization stages of both C (C ii, C iii and C iv) and O are measured may also help distinguish various models for the UVB. Unfortunately, C iv will reside in the NUV channel of COS for absorbers $z \gtrsim 0.12$; the NUV channel is significantly less efficient than the FUV channel (both in throughput and in spectral coverage per exposure). Until better constraints on the UVB are available, it seems important that elemental abundance studies of low-z IGM absorbers consider variations in the assumed energy distribution of their adopted UVB when deriving metallicities.

Based on their measurements of H i, C iii and O vi, Danforth et al. (2006) argued that no single-phase model can appropriately match their observations. Danforth et al. considered only an AGN-dominated spectrum (though not the one adopted here). We have shown that a single-phase photoionization model can match a broad suite of ionic column densities in the present absorber. Other studies have shown that pure photoionization can be made consistent with the ionization characteristics of a significant fraction of the low-z O vi absorbers. For example, Tripp et al. (2008) showed that the O iv/H i and O iv/C iii column density ratio in a large sample of absorbers could be explained by simple photoionization models. In their simplest models, they assumed the absorbers have densities consistent with hydrostatic equilibrium in the low-z IGM (following Schaye 2001) and could match the full range of O iv/H i ratios if admitting a significant dispersion of densities about the mean, a range of metallicities and/or spatially varying UVB intensity and shape, none of which is ruled out at this point. Matching the C iii/O vi ratio in the few absorbers for which Tripp et al. had measurements of that ratio required a departure from the hydrostatic assumption, but their assumptions were still reasonable in the context of the IGM.

Thus, Danforth et al. (2006) conclude photoionization is unlikely on the basis of a photoionization model matching an ensemble of absorbers with a small number of ionic measurements to ionization models that use only one UVB. Meanwhile, Tripp et al. (2008) come to opposing conclusions, finding that photoionization may explain the conditions in an ensemble of absorbers by comparing a wide range of models using different UVB and density assumptions to an ensemble of O vi and C iii measurements. It seems very difficult, given the work on the present absorber, to rule out either photoionization or collisional ionization in such a broad range of absorbers, especially given the small number of ions typically measured and the large number of potential model assumptions.

Danforth & Shull (2008) have presented measurements for a broader range of ions, including C iii, C iv, N v, O vi, Si iii and Si iv, in a survey of low-z absorbers. On the basis of an intercomparison of the various ionic ratios, these authors argue that O vi and N v are
reliable tracers of the WHIM, while C\textsc{iv} may arise from either collisionally ionized or photoionized material. The rest of the ions they argue are relatively good tracers of photoionized matter. We feel that detailed models of the individual absorbers are likely required to determine whether this is truly the case (e.g. Prochaska et al. 2004; Cooke et al. 2008), especially given the range of potential ionizing backgrounds and the potential for mixed ionization processes (photoionization and collisional ionization). In particular, we do not find the argument that the slopes of the frequency distributions in O\textsc{vi} and C\textsc{iii} differ a strong argument for the dominance of collisionally ionized O\textsc{vi}, since a distribution of densities, ionization parameters and local shape of the UVB may provide for much of the difference. We are not arguing that all of the O\textsc{vi} is photoionized, but rather that it may be difficult to tell even in absorbers with observations of a wide range of ions.

Thus, while there is strong evidence that some of the O\textsc{vi} absorbers are associated with hot, collisionally ionized gas (e.g. Tripp et al. 2001; Richter et al. 2004; Savage et al. 2005), a significant fraction of these systems may be strongly influenced by photoionization, like the present system, which requires ∼25–100 per cent of the O\textsc{vi} to be photoionized. These populations are not exclusive given the multiphase nature of some absorbers and the possibility that some trace moderate temperature (T < 10⁴ K) photoionized gas that is mildly shock heated or that has cooled from higher temperatures (e.g. models discussed by Furlanetto et al. 2004; Kang et al. 2005; Oppenheimer & Davé 2009 and others). Tripp et al. (2008) present temperature estimates for a number of the well-aligned systems in their sample. For those absorbers with T < 10⁴ K, a fair number seem to have temperatures somewhat higher than one would expect from pure photoionization, suggesting an extra source of heating that would likely impact the ionization as well. These measurements suggest a mixture of processes could be at work in some absorbers, although photoionization is likely a strong component for a large fraction of the aligned systems. It is not yet clear what the mixture is like in the multiphase absorbers so categorized due to differences in the H\textsc{i} and O\textsc{vi} profiles.

Prochaska et al. (2004) have noted an apparent anticorrelation between the ionization parameter for the cloudy photoionization model best fitting the metal column densities and the H\textsc{i} column of an absorber, a result also seen by Lehner et al. (2006) in a larger number of absorbers along several sight lines. This can be understood in part if the H\textsc{i} column is a rough measure of physical density of the absorber (e.g. Schaye 2001; see discussion in Prochaska et al. 2004). The relationship seen in these earlier works will certainly depend on the adopted ionizing spectrum, since the two UVB spectra investigated here give significantly different ionization parameters. However, while these studies adopt a Haardt & Madau QSOs-only spectrum, if this result is directly tied to the physical density of the absorption, the relationship should still hold if galaxies contribute to the ionization. While some studies have suggested the presence of this correlation implies the absorbers are purely photoionized, our multiphase models show that this conclusion is not necessarily valid. In this absorber, it is not possible to distinguish between pure photoionization or a mixture of photoionization with collisional ionization; furthermore, the photoionized component of the multiphase models has nearly the same ionization parameter as the pure photoionization model. Thus, the correlation likely does not rule out a contribution to those absorbers from collisional ionization, although it may suggest photoionization dominates the ionization, as in the absorber studied in this work.

An important remaining question is how one might distinguish multiphase models such as those with results summarized in Section 4.3 from the pure photoionization models of Section 4.2. While the aforementioned ionization parameter–H\textsc{i} column relationship may not discriminate between these models, there are several promising options. For the current absorber, C\textsc{iv} has significant power to discriminate between these classes of models. The ratios C\textsc{iv}/C\textsc{iii} and C\textsc{iv}/O\textsc{vi} are significantly different for photoionization models compared with the multiphase models due to the strong variations in these ratios as a function of temperature in the collisionally ionized gas. At low temperatures, the C\textsc{iv}/C\textsc{iii} ratio in our multiphase models is nearly the same as the QSOs+galaxies UVB photoionization model. However, for temperatures log T ≳ 5.3, this ratio is approximately two to 15 times higher for the multiphase models than the photoionization models. Conversely, the C\textsc{iv}/O\textsc{vi} ratio is within a factor of 2 for both models at log T ≳ 5.3, while at lower temperatures the multiphase models predict a C\textsc{iv}/O\textsc{vi} ratio factors of ∼4 to >1000 higher than the pure photoionization models (which give N(C\textsc{iv})/N(O\textsc{vi}) ∼ 0.6 to 0.2 for the QSOs and QSOs+galaxies UVB photoionization model. This large difference in models at low temperatures is due to the strong fall off in O\textsc{vi} ionization fraction with decreasing temperature over this range. These large differences for models in which a small fraction of the gas is associated with the collisionally ionized phase is due to the very large (or small) ratios of C\textsc{iv} compared with the other two ions in collisionally ionized gas. For example, at log T = 5.45, the C\textsc{iv}/C\textsc{iii} ratio in CIE is expected to be ∼60 compared with ∼2 in the QSOs+galaxies photoionization model. Thus, even though the collisionally ionized phase is limited to ∼50 per cent of the total hydrogen at this temperature (see Fig. 9), it contributes >90 per cent of the C\textsc{iv}.

Danforth & Shull (2008) studied the integrated column densities of C\textsc{ii}, C\textsc{iv} and O\textsc{vi} for a number of absorbers, finding C\textsc{ii}/C\textsc{iv} ratios of ∼1 and C\textsc{iv}/O\textsc{vi} ratios consistent with ∼0.25 (both with a quite large scatter). Both of these ratios are consistent with our photoionization models, though it may be dangerous to draw conclusions based on these two average ratios, which rely on different samples of absorbers, without attempting models of the ionization to match the full range of ionization states in each absorber. Indeed, Danforth & Shull conclude that the O\textsc{vi} mostly arises in collisionally ionized gas on the basis of their comparisons. Danforth & Shull note that the correlation of C\textsc{iv} with both O\textsc{vi} and C\textsc{iii} is not particularly strong, and they use this to argue that the observed C\textsc{iv} in their sample may arise from both shock-heated and photoionized gas (traced by O\textsc{vi} and C\textsc{iii}, respectively, in their argument). A significant population of multiphase absorbers where the mixture of phases varies could presumably also provide for such a lack of correlation.

Future observations with the COS on board HST should provide significantly higher S/N observations of QSOs than have been possible with STIS, albeit at lower spectral resolution. This can provide better limits and detections of weak absorption lines for some sight lines with quite low S/N STIS observations, such as the PKS 0405–123 sight line, allowing stronger constraints on the models. In the present absorber, for example, O\textsc{iii} already provides important constraints on the single-phase collisionally ionization models. Better observations of this transition will begin to limit the photoionization and multiphase models more severely.

The metallicity of this absorber is quite high for both UVB spectra adopted here. There are significant systematic uncertainties associated with our estimates, but [O\textsc{ii}]/H\textsc{i} ∼ −0.6 or −0.15 are both high compared with the canonical mean of [O\textsc{ii}]/H\textsc{i} − 1. The high metallicity and great strength of the O\textsc{vi} absorption both favour an origin of this absorber near to a galaxy, although the H\textsc{i} column
and estimated densities are not large. Given the discussion in the previous section, if this absorber were associated with a galaxy, it would likely be a sub-$L_*$ system.

6 SUMMARY

We have presented FUSE and HST/STIS ultraviolet absorption-line observations of the $z = 0.495096$ absorber towards the QSO PKS 0405$-$123. We have measured the column densities of H$_1$, C$_{\text{III}}$, N$_{\text{IV}}$, O$_{\text{IV}}$, O$_{\text{V}}$ and O$_{\text{VI}}$ and placed upper limits on the column densities of another seven ions. We use these measurements to study the ionization processes at work in this absorber and estimate its metallicity.

The most important results of our work are as follows.

(i) This absorber shows very strong O$_{\text{VI}}$ absorption with no detectable Ne$_{\text{VII}}$ or Mg$_x$. There is no direct evidence for a strong component of gas with temperatures $T \gtrsim 5 \times 10^5$ K as expected if it traces the largest mass of missing baryons in a WHIM. However, the limits to the amount of material depend strongly on the temperature (see Fig. 10). This system would not likely be detectable in X-ray absorption.

(ii) We have modelled the broad range of ions covered by our data using a number of collisional ionization and photoionizations models. This absorber can be modelled as purely photoionized gas with $[O/H] \sim -0.6$ if the ionizing UVB includes a significant contribution from photons associated with star-forming galaxies and $[O/H] \sim -0.15$ if the UVB does not include a significant contribution from galaxies. These metallicities are robust to the inclusion of a collisionally ionized phase.

(iii) The ionization of the absorber may also be well described by multiphase models in which the photoionized gas in the absorber is complemented by a contribution from hot ($T \gtrsim 3 \times 10^5$ K), collisionally ionized gas. The strong O$_{\text{VI}}$ in this system may trace a photoionized phase, a collisionally ionized phase or a mixture of both. In this case, the metallicities are still consistent with those from a pure photoionization model.

(iv) The uncertainties in the spectral shape of the ionizing UVB give rise to significant systematic uncertainties in the derived metallicity of the absorber, of the order of 0.5 dex or a factor of 3 in this case. Such uncertainties should be fully considered when studying the metallicity distribution, ionization and baryon content derived from metal lines of the low-$z$ IGM.

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